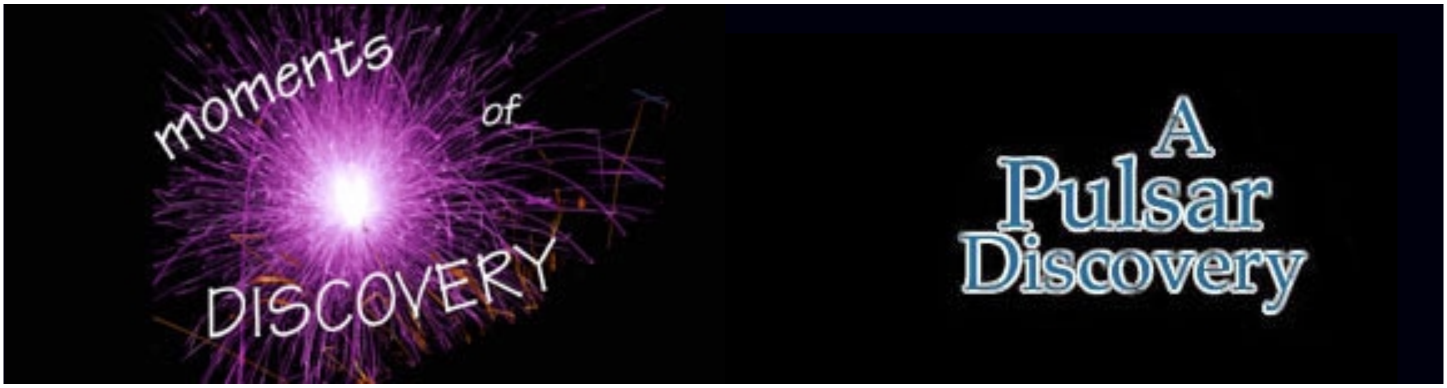

Note to teachers

The overall goal in this exhibit is to give students and teachers a glimpse into a moment of discovery. The discovery of optical pulsars may be the only example of a significant discovery documented by a tape recorder left running for other purposes. The listener is privileged to hear an event as it happened, not the staging of an event.

This exhibit allows students and teachers to recognize scientists as people. The thrill of discovery provides a human element to which everyone can relate. As Cocke and Disney check their results and share their excitement, they are people engrossed in science, not humorless, unfeeling machines recording data.

This exhibit also provides a compact view of the scientific process in operation. Experimental science is presented in a true context. The astrophysicists are constantly observing, manipulating equipment, and then repeating the observation in order to be certain of their results. Mathematics, data and instruments are all checked. Only after they have tried every way they can think of to make their discovery "go away," and still find it staring at them, are the scientists satisfied.

This exhibit can also be an opportunity for professional development. Science teachers can strengthen their background in pulsars and neutron stars -- one of the most fascinating new fields of astronomy -- through self-study of the module and linked Web sites. Teachers can better understand the struggle of scientists to understand the nature of this interaction as they listen to the scientists themselves describe their involvement.

In an astronomy course: The unit can be used during a discussion of stellar evolution or at any other point where the topic of pulsars is specifically addressed.

In a physics course: The unit can be used in connection with discussions of gravity, density of matter, conservation of angular momentum, or especially when discussing the different forms of electromagnetic radiation. It may also be used as a brief excursion into scientific discovery or scientific method.

In a history or philosophy of science course: This unit can be used as a true account of one type of discovery in science.

We need your feedback so we can do more exhibits like this! Both our funding and our enthusiasm could falter if we don't hear from users. Please e-mail us at chp@aip.org or use the online form (at https://webster.aip.org/forms/feedback.htm) to tell us how useful this was to you (a brief word is great, comments and suggestions better still).

Contents of This Unit

Audio clips and accompanying text: These are central to every format of presentation. Test trials of these materials showed that in classroom use, it is best to have students read the script simultaneously with listening to the audio, rather than listen to the audio alone. Permission is granted to the instructor to make photocopies of the script for the purpose of providing every student or every pair of students with a script, for classroom use.

The exhibit can conveniently be broken into two segments. The first part includes narration and excerpts from interviews with Cocke and Disney relating the events leading up to the discovery. The second part is the audio recording of the scientists on the night of the discovery.

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Articles:

- The unit includes original research papers excerpts—
Hewish, Bell, *et al.*, "Observation of a Rapidly Pulsating Radio Source," *Nature* vol 217, p.709 (24 Feb. 1968).

- Cocke, Disney, and Taylor, "Discovery of Optical Signals from Pulsar NP 0532," *Nature* vol. 221, p. 525-27 (8 Feb. 1969).

- a primary resource—
extract from laboratory notes of John Cocke, night of 15 Jan. 1969.

- articles on the physics of pulsars—
DiLavore and Wayland, "Pulsars for the Beginner," *The Physics Teacher* vol., p.232-237 (May 1971).

- media account—
"Pulsar Detected Optically," *Sky and Telescope*, p. 135 (March 1969).

- and additional readings—
Table of contents from Davies and Smith, ed., *The Crab Nebula*, International Astronomical Union Symposium no. 46, Aug.5-7, 1970 (Dordrecht: S. Reidel; N.Y.: Springer Verlag, 1971).

- Application for time on a telescope (1983).

Exercises: The unit presents suggestions for assorted activities, demonstrations, questions, problems, and experiments.

These exercises have been labeled as Discussion, Investigation, or Research.

—Discussion exercises (**D**) require no preparation or reading by the student. These exercises can be used for class discussions or as homework assignments.

—Investigation questions (**I**) require the reading of an article which is included in this unit, or the use of reference works such as an encyclopedia. Instructors can make the articles available for a more comprehensive assignment.

—Research questions (**R**) require library work. Some of these exercises are quite extensive and should be treated as long-term projects.

The physics/astronomy exercises are identified as simple or complex.
—A simple exercise (**S**) requires no background material and is a suitable class or homework assignment.

—A complex exercise (**C**) requires that the student have access to a physics text or to some laborabory equipment.

Bibliography: The unit includes an annotated bibliography for instructor and student use.

The National Standards

The National Science Education Content Standards "outline what students should know, understand and be able to do in the natural sciences over the course of K-12 education." Although most science teachers are aware of the subject matter understandings (i.e., Physical Science Standards) in their respective disciplines, too little attention is devoted to the categories of:

- Science in personal and social perspectives

- History and nature of science
- Science and technology
- Science as inquiry

This exhibit provides material that speaks to these dimensions of science content knowledge as well as the required Physical Science Standards. This exhibit is an excellent vehicle by which to bring the full Content Standards to the science classroom.

Physical Science and Earth & Space Science Standards: The Pulsar Discovery includes some subject matter understandings from both the 9-12 Physical Science and Earth & Space Science Standards. The size of the pulsar leads to exercises concerning rotation rates and nuclear forces and magnetic fields. The decrease in the rate of spinning provides an example of energy conservation. The exhibit also provides insight into stellar evolution.

Science in personal and social perspectives: The investigation of pulsars appears not to have direct impact on the health or well-being of our society. Students should have an opportunity to discuss some of the issues which policy makers must address: Should such investigations be supported with tax dollars? Who makes decisions on which proposals will be funded and at what cost? Should research with pre-determined applications be the only ones that are funded? Should pulsars only be studied if they can produce a better clock?

History and nature of science: The Pulsar Discovery unit and related teachers' guide provide an example of curriculum materials that support this content standard. The script and exercises emphasize Science as a Human Endeavor, speak to the Nature of Scientific Knowledge and provide Historical Perspectives. A student gets a rare glimpse into the creation of new knowledge as a real-time tape provides an account of scientists with their guard down.

Science and technology: The scientists involved in the discovery of the pulsar note the interplay of science and technology in various discussions. Cocke and Disney needed the "ideal piece of equipment … belonging to Don Taylor." In contrast to the sophisticated equipment, they had to build for themselves a tiny diaphragm out of a piece of aluminum foil.

Science as inquiry: One component of the inquiry content standard is that students should understand that scientists engage in inquiry and the nature of that engagement. In the Pulsar Discovery, students learn about the types of questions that scientists ask, how they rely on technology to gather data, how mathematics is used and how scientific explanations must adhere to specified criteria. They are also introduced to different kinds of investigations and communications of scientists. Students get to examine the laboratory notebook as a primary source illustration of the artifacts of science as inquiry.

Lesson Plans

The instructor can allot no class time:
The students can benefit from the audio through independent study. Students visit the exhibit online and perform the exercises assigned by the teacher. For example, one exercise can be chosen and given to the entire class. Or different exercises can be assigned by the first letter of the student's last name. Or, as a third alternative, a group of exercises can be offered and each student can choose which avenue to explore.

The instructor can allot one class day:
—Students can visit the exhibit as a group during class time. In this case, scripts should be available to every student or pair of students. Permission is granted to the instructor to make photocopies of the text for the purpose of providing every student or pair of students with a copy for classroom use. Students may be given one homework assignment prior to listening to the audio and one after listening to the audio.

The uninterrupted audio track and all the rest of the unit can be purchased at nominal cost on a CD-ROM by filling out the order form online at http://www.aip.org/history/mod/order.html which can be played in class or made available to individual students who have access to a computer.

MOST TEACHERS WILL PROBABLY FIND THE ABOVE THE BEST WAY TO USE THE UNIT.

OR—Teachers may elect to have students view the exhibit independently (see above) and later use class time for discussion and exercises.

The instructor can allot two class days:

DAY 1: Students view the first half of the exhibit.
The remainder of the class is used for comments on one or more discussion questions, such as those in the accompanying list.

A homework assignment should be chosen, for example from the accompanying list, reflecting teacher or student interest.

DAY 2: Students view the second half of the exhibit.

The beginning of the class may center on reviewing homework or on fresh questions chosen by the instructor. The remainder of the class time may be spent on discussion questions emphasizing the exhibit as a whole.

Homework should be assigned. This might require the reading of an article included in the unit, or library research.

The 5E Model

The 5E model of good science instruction recommends that teachers structure the lesson so that it includes the following components: engage, explore, explain, elaborate and evaluate.

In using the Pulsar Discovery exhibit, teachers can adopt the 5E model in the following manner:

Engage: Students should be questioned about the size of astronomical objects like the Moon, Earth, Sun and other stars. Students at the high school level can still be expected to harbor misconceptions concerning the rotation and revolution of the Earth, no knowledge of the rotation of the Sun, and little knowledge of how the solar system is held together. The questions of scale can engage students and provide a basis for a better appreciation of the pulsar. Without such a preliminary discussion, students will not understand why the discovery of the pulsar came as such a shock to scientists the world over. Students should be given the opportunity to articulate their prior conceptions. Teachers should be attentive to the students' understanding so that the subsequent instruction can provide a rationale for students to continue their prior beliefs or to replace them based on their study.

Explore: Students can read and listen to the script and begin to explore the events leading to the discovery of the optical pulsar. They can continue their exploration by responding to some of the exercises including the brief laboratory activities on the use of a manual stroboscope and the creation of a diaphragm. They can also review the notes that Disney recorded on the night of the discovery.

Explain: Students should study the articles that are included in the exhibit. The original research articles may be a bit difficult in their entirety but should be attempted. Science students get too few opportunities to read any original literature. The other articles and essays were chosen as part of the exhibit because of the different perspectives that they bring to our understanding of pulsars.

Elaborate: Students should have the opportunity to apply the knowledge from the script to new situations. Students should review the Table of Contents from a Crab Nebula symposium held just a few years after the discovery of the first pulsar. They can complete exercises related to the physics of pulsars as well as exercises related to the tape recording, the interaction of the scientists, and the scientific processes that were used to insure that a mistake had not been made.

Evaluate: Many of the exercises can be used as evaluative tools of what students understand and are able to do. The teacher should help students set the criteria for successful achievement. What is the level of expectation in terms of the physics problem solving or the related research items? Evaluations can also include group projects that require students to produce informational pamphlets, to perform or create additional physics simulations, or to compose an essay or play that draws out the human and scientific elements in the pulsar discovery.

The 4 Question Model

The 4 Question model of science instruction requires that students be able to answer the following questions:

- What does it mean?
- How do we know?
- Why do we believe?
- Why should I care?

In using the Pulsar Discovery exhibit, teachers can adopt the 4 Question model in the following manner:

What does it mean? Students should be able to provide a sense of the size of the pulsar and the rotation rates of the pulsar. They should also be able to explain the decrease in the rotation rate using conservation laws. They should also be able to explain the content standards of the National Standards in the domains of inquiry, technology, society and history.

How do we know? We know because we made observations. How were Cocke and Disney able to measure the rotation rate of the pulsar? How were they sure that their data were accurate? Why was it important to know the expected period of 33.2 milliseconds before beginning the experiment? How would the experiment have changed if they did not know the period from the outset?

Why do we believe? Why do we believe that the pulses are naturally occurring and not the result of an extraterrestrial being trying to contact us? (The first pulsar was initially suspected to be such contact.) The size of the pulsar demands that the origin be a neutron star. The models for stellar evolution must allow for the incredible compression of matter. Calculations of forces, stellar evolution, conservation laws and a mechanism for explaining our observations must all hold together if we are to believe in the optical pulsar results.

Why should I care? The pulsar has very little relevance to our lives. Similarly, the electrical investigations of Faraday, Ampere, Maxwell and Hertz had little relevance at that time. If scientists like those mentioned had been required to work on improving modes of communication, the discovery of radio waves and the electromagnetic spectrum would probably not have occurred. Their interests and investigations led to the development of radio, television, and the transistor (http://www.pbs.org/transistor/) along with all of the accompanying social changes. There are similar examples of pure research into the behavior of atoms leading to discoveries that found applications in MRI and other medical technologies. Who should decide what research should be funded? Why should we care about pure scientific research?

A WORD TO THE WISE
Physics teachers may well lack experience in leading discussions. We all know, however, that it is not possible nowadays to think about science without taking account of different viewpoints on social questions. Since the interaction of science and society is often taught only superficially in social studies courses, science teachers need to explore the issues. It is recommended that teachers have a number of discussion questions created or chosen from those provided, so that if one does not develop into a useful class dialogue, a second or third question can be presented.

History teachers frequently lack experience with science demonstrations, problem solving, or explanation of scientific theories. We all know, however, that the citizen can no longer separate understanding of modern history from basic ideas about science itself. Since many students have a very rudimentary science education, a unit in the history of science may be one of their few encounters with scientific reasoning, and it is important to be sure they can follow the logic of the science itself. It is recommended that the instructor test a demonstration before presenting it to the class. Similarly for science problems, a previously worked out solution or explanation will always lead to a better class presentation.

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Suggested Exercises

S

1. The maximum possible size of a pulsar can be roughly determined from the fine structure of the pulses emitted, reasoning as follows.

If the sun were to turn off all over instantaneously, we would not see the light cease instantaneously, for the last light from the near side of the sun would reach the earth a little sooner than the last light from the far edge of the sun. Given that the sun's radius is $6 \text{ X } 10^8$ meters, how much time would elapse between the arrival of the two bits of light?

A flash from a pulsar may have a fine structure with typical time of rise and fall around 30 the flash.

2.Pulsars are thought to be rotating neutron stars. The pulses probably emanate from the magnetic poles, which rotate with the star (as with the earth, these poles may not be aligned with the axis of rotation). The light goes straight out from the poles, like a beam from a searchlight, and on every rotation, the beam may sweep across the earth. **S**

What would we see if the magnetic poles of the pulsar were exactly aligned with its axis of rotation, and pointing toward the earth?

From this "lighthouse" model, would you conclude that there are many more pulsars than we have observed? Why? Construct an equation for the number of unobserved nearby pulsars, in terms of the number of nearby pulsars that have been observed. (Before writing the equation, you will need to define some symbols in terms of the geometry of a typical pulsar beam.)

3.The energy of a pulsar's emission is drawn from the pulsar's rotation, resulting in a slowing down of the rotation rate. This slowing down has been measured. The Crab pulsar, which has a rotation period of 33 milliseconds, is slowing at the rate of 4.2 X 10^{-13} seconds per second. **S**

What is the rate of slowing in seconds per year? If you used this pulsar as a clock, how much time would pass before you were "slow" by one minute?

The age of a pulsar is given approximately by the equation

$$\text{Age} = 1/2 \quad \frac{T}{T'}$$

where T^1 is the period of rotation and 1/T is the rate of change in the period. Using this equation, how old is the Crab pulsar?

4. LABORATORY EXERCISE: measuring short time intervals using stroboscope. **C**

The principle of the stroboscope can be demonstrated with a slowly blinking light, such as a spotlight on the street. If you blink your eyes at the same rate as the light, you can make it seem to yourself as if the light is always off, by having your eyes closed whenever the light is on. Or you can make it seem as if the light is always on. By controlling the way you look, you can make something that moves in a repetitive way "stand still." This is precisely like the way Taylor's electronics helped Cocke and Disney make the pulsar's blinking "stand still" so they could see it.

The hand stroboscope lets you do this for things that move more rapidly than the eye can blink. It is a disk with several equally spaced slits. As the disk is rotated in front of the eye, the eye catches a glimpse of the moving object, which can appear to be stopped. For example, you may look at a rotating circular saw with a red spot painted at one position. If you make the spot seem to stop by looking at the saw through a hand stroboscope of 6 slits, turning at 35 revolutions in 5 seconds, you can calculate: .,

$$\frac{\text{35 revolutions}}{\text{5 seconds}} \text{ X } \frac{\text{6 slits}}{\text{revolution}} = \text{42 slits per second}$$

therefore the saw is rotating at 42 revolutions per second.

(a) Could the saw also be rotating at 84 revolutions per second? at 21 revolutions per second?

(b) If the spot on the circular saw appears to move slowly backward when seen by a stroboscope, is the stroboscope rotating a little faster or a little slower than the rate that will hold the spot still? Explain. (This is precisely similar to Cocke and Disney's concern with holding the pulse in the middle of their screen.)

(c) A television camera looked at the Crab pulsar (whose period is .033 seconds) through a stroboscope. If the strobe had 8 slits, at what rate should it rotate to make the pulsar seem always lit up?

(d) Use a hand stroboscope to measure the rotation rate of an electric fan; the vibration rate of a bell.

(e) What do you see if you look at a fluorescent light through a stroboscope? (The effect can sometimes be seen by looking at a rotating object, such as an electric fan or the gears on a rotary hand drill, under a fluorescent light.)

5. Much as students make applications for college, astronomers must make applications to use major telescopes. Read the "Application for Time on a Telescope" form used by a large observatory. Comment on each portion of the form. Specifically, why does the committee that decides who gets telescope time need an answer to each question? Imagine that you are Disney or Cocke and fill out the application in order to convince the committee to give you time to search for an optical pulsar. **D,I**

6. **LABORATORY EXERCISE:** Make a diaphragm. Cocke and Disney described a diaphragm that they needed to observe the pulsar (so their light-detecting device would not be swamped by the light of other nearby stars). They made it with a razor and aluminum foil. **I**

(a) Comment on this aspect of a modern experiment. Should they have used more refined apparatus? How would their story have been different if they had required a special diaphragm that took a team of technicians a month to build?

(b) Make a diaphragm ten times the size of theirs: a square hole in foil exactly 1 mm x 1 mm. Then try for one 0.1 mm x 0.1 mm.

(c) Can you think of a better way for making such a diaphragm at home? (One possibility: coat a piece of glass with paint, let it dry, and scratch some of the paint away.) Try other methods.

7. R. Willstrop of Cambridge, England, was taking data from the Crab pulsar months before Cocke and Disney. However, Willstrop needed a large amount of computer analysis of his data, so he was not able to announce the "discovery" of an optical pulsar until after Cocke and Disney. Who should get credit for the discovery? What difference does it make who gets the credit? Some sociologists believe that credit for a discovery is the chief reward a scientist strives after. How important to progress in science was assignment of credit in the pulsar story? **D,R**

A student, Jocelyn Bell, was first to observe a radio pulsar while analyzing data—she noticed something peculiar that nobody else had paid attention to, and hunted down its source. But a Nobel Prize was awarded to Anthony Hewish, who had assigned her the task and who had built the radio telescope. There has been some controversy over whether the prize award was fair. Compare this with the assignment of credit in the optical pulsar story. How much credit should go to the builder of an instrument, like Hewish or Taylor? How much to the person who designs a research program, like Hewish, and how much to the person who carries it out in a creative way, like Bell? Does it matter?

8. Consider the following circumstances of the optical pulsar discovery: (a) Cocke and Disney meet; (b) Taylor has a suitable apparatus; (c) a new fast pulsar has recently been discovered (it turns out that of the hundreds of pulsars observed with radio telescopes, only a handful are readily seen with ordinary light); (d) they get extra observing nights because a colleague's wife is ill; (e) they find a math error when they recompute their values; (f) they hold PhDs, representing years of hard training in science. **D**

How much luck was involved in the discovery? How much hard work? In your answer, refer to the above circumstances as well as any others that seem relevent.

A favorite motto of scientists was stated by Louis Pasteur: "In the realm of observation, chance favors the prepared mind." In what way does or does not this saying apply to the pulsar story?

9. Optical pulsars help us understand neutron stars, a late stage in the life cycle of some stars. What is the significance of Cocke and Disney's work? If we understood the life cycle of stars better—so what? Should research of this type be supported with tax dollars? **D,R**

10. When Taylor got the excited phone call from Disney and Cocke, he was skeptical at first. Would most scientists have felt that way? How important is skepticism in science? How skeptical should you be when you hear something from (a) a textbook; (b) a famous scientist on television; (c) a scientist on television identified as a member of a "public interest" group; (d) a television reporter? Would a good scientist be more or less skeptical than you of each of these sources? How do scientists finally decide whether what they have been told is true? **D,R**

11. Compare the audio recording of the discovery, the paper describing the results in *Nature*, and (if you can find one) a newspaper article announcing the discovery. Which comes closest to describing what was in fact discovered? Which is most objective? Is anything entirely objective? **I,R**

12. The official communication of the discovery in *Nature* is written in a highly stylized form. Why is this form used? **I**

Take a long, hard look at some everyday phenomenon (for example, water emptying from a sink, or a sunset) and imagine that it has never been observed before. Write (a) a paper in scientific style, and (b) a letter to a friend about your "discovery." What purposes are served by each style?

13. The audio recording that you have listened to was pieced together from interviews with three people and from the tape made at the time of the discovery. In what ways is the tape made at the time likely to be more truthful than the accounts recorded a decade later? In what ways might the tape made at the time be *less* useful to understanding what happened? Some historians think it is a waste of time to interview people about what they did many years ago; these historians spend their time studying old correspondence and other writings recorded near the time of the events they study. Other historians try to interview as much as possible. Discuss the advantages and disadvantages of each approach. Use some examples from the optical pulsar story. **D,R**

14. If you could stand on a neutron star, how far away would the horizon appear? **C**

15. Name some objects that rotate at about the same speed as a pulsar. Which have the most stable rate of rotation? Why? **C**

16. Review the description of the environment as Disney saw it on his way to the observatory. Is this your impression of what a scientist would notice? Is it different from what a non-scientist would notice? **D**

17. We know that ice skaters can spin faster by pulling their arms in: the angular momentum is constant, but the decreased radius produces an increased rotation rate. Calculate the angular momentum of our sun (radius 6 X 10^8 meters, period of rotation 25.3 days), making an arbitrary assumption about the distribution of mass. Using conservation of angular momentum, calculate the new rotation rate if the sun shrank to the size of a neutron star (radius 10 kilometers = 10^4 meters). How does this compare with the rotation rates of pulsars? **C**

18. If all the mass of the sun were to become a neutron star, what would be its density? (Solar mass = 2 X 10^{30} kilograms.) How does this compare with the density of the nucleus of an atom? If you could get a piece of a neutron star the size of a pea, how much would it weigh on earth? **C**

19. On the earth, the gravitational force at the equator is partly balanced by a centrifugal force which tends to throw things off this spinning planet (that is why the earth bulges slightly at the equator). Find the gravitational and centrifugal forces at the equator of a pulsar 10 km in diameter with a pulse interval of 33 milliseconds. Compare these with the same forces on earth. Would you expect much of an equatorial bulge on a pulsar? **C**

20. Calculate an example of Coriolis forces on the surface of a neutron star, assuming a plausible position and velocity for a moving object. If creatures somehow lived on the surface of the neutron star, would Coriolis forces severely affect their movements? **C**

21. The sun has a magnetic field at the surface averaging about 1 gauss. If the sun were to shrink to the size of a neutron star, the field lines would not escape but would become more tightly wrapped. What magnetic field strength would the neutron star have? Does your result seem reasonable? If creatures lived on the surface of the neutron star, and if their bodies had magnetic properties like our own, would they have to take magnetic field lines into account in their movements? **C**

(*Note for the teacher:* There is a science-fiction novel by the astrophysicist Robert L. Forward, *Dragon's Egg*, Ballantine: 1980, which imagines life on a neutron star. The "biochemistry" is made of combinations of nuclei, which can exist in a very shallow surface zone. The creatures are blobs a few mm across. While gravity is too great for them to throw objects, anything they roll is noticeably affected by Coriolis forces. Magnetic field lines are far more important: at the magnetic equator, a creature is pulled out into a cigar shape; it can move along field lines easily, but across them only with great difficulty.)

22. Find the Crab Nebula on a star map. Can you find it in the sky during XXX? (*Note for the teacher:* fill in month when exercise is assigned.) **I**

23. In November 1982 a new pulsar was discovered, PSR 1937 + 214, better known as "the millisecond pulsar." Its period is 1.56 ms, that is, a frequency of 642 pulses per second, twenty times the rate of the Crab pulsar. Calculate the gravitational and centrifugal forces for this pulsar, assuming a diameter of 10 km. What is the velocity at the equator? Is this close enough to the speed of light so that useful calculations would have to call upon the equations of special relativity? **C**

24. The "South Preceding" star in the Crab Nebula (the Crab pulsar) was recorded on a photographic plate made in 1899, and preserved since then. State some questions that could be answered by comparing this old plate with a recent one, and that could not be answered by a recent plate alone. **I**

Old astronomical photographic plates are worth preserving for scientific use, whereas old laboratory measurements in physics are of little scientific value—because a physicist can always measure a physical quantity anew, and usually more precisely than the first time. Astronomy, but not physics, is in part a "historical science." Name some other "historical sciences." How are they like the study of human history? How are they unlike it?

25. Following the audio part of the exhibit, outline the steps in the process of the optical pulsar observation. Include "null" observations, checks of various kinds, changes in the data accumulated, repetitions of earlier trials. From this outline and your general ideas about scientific process, answer the following: **I**

(a) How skeptical are Disney and Cocke?

(b) Why does Taylor tell them to sit on their results?

(c) Does this case agree with your ideas about "good" scientific method? Explain your answer.

(d) Examine the sample from Cocke's notebook. Does this agree with your ideas about how "good" scientists record data?

26. Inspect the page from the proceedings of a pulsar conference. Using this as evidence, estimate about how many people were working on pulsars at that time? State your reasoning. **I,R**

Some scientific subjects are studied only occasionally by people who soon move on to other subjects. Other subjects may become institutionalized fields, first with conferences, then perhaps with textbooks and university professorships, finally with entire journals and scientific societies dedicated to the field. How far along this series of steps would you expect the study of pulsars to go, and why? Name some things that might influence whether a subject of inquiry will attract the full-time attention of many hundreds of researchers?

27. Define the Doppler effect in general. What effect did it have on the search for an optical pulsar? **R**

28. Suppose a pulsar is about equally hard to detect at radio and at optical light frequencies. Atmospheric absorption of radio and optical frequencies is slight, and instruments to detect their energy are of roughly equal sensitivity. A typical major radio telescope has 50 times the diameter of a major optical telescope. **C,R**

(a) Roughly what is the ratio of the energy the pulsar emits in radio frequencies to the energy it emits in optical frequencies?

(b) Suppose the pulsar emits the same amount of energy in X-ray frequencies as in optical frequencies, should this be very easy or very hard to detect? Give two reasons for your answer.
(*Note for the teacher:* X-rays from pulsars have been detected by satellites above the atmosphere.)

(c) Why can a radio telescope be built much larger than an optical one? What sets the limit on how big a radio telescope can be?
(*Note for the teacher:* The largest radio telescope is at Arecibo, Puerto Rico, and fills a natural hemispherical depression 305 meters in diameter.)

A larger project for an advanced student or student team can be made from four Web exhibits which all describe "moments of discovery:" nuclear fission, an optical pulsar, the electron, and the transistor. The student(s) should study all four exhibits and discuss similarities and differences -- socially in terms of individuals, scientific institutions, and communication, and scientifically in terms of technologies and thought processes. Students can review the lists of questions in the Teachers' Guides for ideas on directions to follow (perhaps too many!). The students should conclude with general statements about things that seem necessary for all discoveries, at least in modern physical science.

Additional Reading and Links

Unless otherwise noted, the level is appropriate for middle-school students and above. Popular books and textbooks are being published at such frequency that any bibliography is quickly out of date. The references that are listed here serve as a general view of what is usually available..

Web Sites

Neutron Stars and Pulsars
http://imagine.gsfc.nasa.gov/docs/science/know_l1/pulsars.html
Brief information from NASA's Goddard Space Flight Center, with resources and a "Teachers' Corner".

The Sounds of Pulsars
http://www.jb.man.ac.uk/~pulsar/Education/Sounds/sounds.html

Sound clips give a physical feeling for the rapid spinning of these incredible objects.

Astronomy, Astronomers, and the Steward Observatory
http://www.as.arizona.edu/steward/
Good general information on astronomy and astronomers, plus what's up at the University of Arizona's Steward Observatory today: telescopes, people, research.

Astronomy at Different Wavelengths
http://www.ipac.caltech.edu/Outreach/Multiwave/
From Caltech, a readable explanation of how astronomers make use of many kinds of telescopes to study objects in wavelengths from radio to x-rays.

The Princeton Pulsar Group
http://pulsar.princeton.edu/pulsar/multimedia.shtml
The group offers some basic pulsar information and visual and sound clips for the public. The site also lets you see how they carry on their work (scientific papers, telescope schedules, etc.).

Jodrell Bank Observatory Pulsar Group
http://www.jb.man.ac.uk/~pulsar/
Another major research group in action, including college-level course materials complete with technical equations and a bit of history, and more links.

NASA Space Link
http://spacelink.msfc.nasa.gov/
An educators' gateway to NASA's huge resources, mostly on spaceflight and the planets but including astronomy.

NASA's Astronomy Picture of the Day
http://antwrp.gsfc.nasa.gov/apod/
Fascinating browsing on all astronomical topics.

Readings

- **Levy, David H.** *Skywatching (A Nature Company Guide).* New York:Time-Life Books, 1995.

Bite-size chunks of information on astronomy including historical overview, astronomers today, skywatching guide with constellations etc., and descriptions of astronomical objects including pulsars.

- **DeVorkin, David, ed.** *Beyond Earth : Mapping the Universe.* Washington, DC: Smithsonian Air & Space Museum and National Geographic Society, 2002.

A lavishly illustrated history of cosmology from ancient times to the present, particularly rich in information about instruments. By a leading historian of modern astronomy.

- **Ferris, Timothy.** *The Whole Shebang: A State of the Universe(s).* New York: Simon & Schuster, 1997.

Little on pulsars, but this is among the best-written of the popular-level descriptions of the history and status of modern cosmology, by a premier science journalist. (Note however that the field advances so quickly that within a few years all books get partly out of date.)

- **Kaufmann, William J. III, and Roger Freedman.** *Universe.* New York: W.H. Freeman, 5th ed., 1998.

- **Pasachoff, Jay. Astronomy:** *From the Earth to the Universe.* Pacific Grove, CA: Brooks/Cole, 6th ed., 2002.

These are two of a number of readable and well-illustrated textbooks designed for introductory college astronomy courses, and accessible to an advanced high school student with a strong interest in science. Pulsars are discussed in chap. 23 of Kaufmann/Freedman and chapter 30 of Pasachoff.

- **Lyne, Andrew G., and Francis Graham-Smith.** *Pulsar Astronomy (Cambridge Astrophysics Series, Vol 16).* Cambridge: Cambridge University Press, 2nd ed., 1998

An authoritative technical work for advanced science students and practicing researchers, with a chapter on the history of pulsar discovery.

MAGAZINES: To keep abreast of the latest discoveries in astronomy, consult recent issues of *Sky and Telescope* and *Science News*, both available in most libraries.

Reprinted Articles

George Greenstein, excerpt from *Frozen Star*, New American Library Trade, p.13-31 (May 1985).

CHAPTER

2

The Discovery of Pulsars

By the late 1960's, the idea of a neutron star had been in the air for more than three decades. They were eventually discovered by accident.

The accident occurred in Cambridge, England, in 1967, and it happened when the British astronomer Antony Hewish built a new kind of radio telescope. Hewish was not looking for neutron stars at all. He had no particular interest in them. He was interested in twinkling—or, in more technical terms, scintillation. Hewish wanted to study the scintillation of the radio signals from the quasars. To do so he was forced to build a new kind of radio telescope: one sensitive to the minute, rapid fluctuations the scintillation produced. This telescope, in fact, was the very first capable of detecting such rapid fluctuations in the intensity of a cosmic radio source. Purely by accident the design was ideally suited to the discovery of pulsars. For this discovery, as well as for a lifetime of distinguished work in radio astronomy, Hewish received the Nobel Prize in physics in 1974.

It was not Hewish himself who actually found the first traces of the pulsars. This honor goes to a graduate student, Jocelyn Bell. It was she who first found, in late September of 1967, an anomaly buried within the veritable maze of data produced by the new telescope. Initially she did not know what to make of this anomaly. It hardly seemed real. She called it "scruff."

Bell attempted to pin down its nature by more carefully observing the radio source. The source refused to cooperate. It went away. For two full months she went out to the telescope each day, looking for the scruff, and for two months the radio source remained invisible. Many other scientists—and certainly many other students—would have given up. Bell continued. Finally, in late November of 1967, the radio source reappeared, and she immediately realized that what she had been calling scruff was actually a series of regular pulsations. She had discovered the first pulsar.

Years later, in an after-dinner speech at a scientific meeting, Jocelyn Bell—by then Jocelyn Bell Burnell—described her experiences during that wonderful time.

"I joined [Hewish] as a Ph.D. student when construction of his telescope was about to start," she said. "The telescope covered an area of four and a half acres—an area that would accommodate 57 tennis courts. In this area we put up over a thousand posts, and strung more than 2,000 dipoles between them. The whole was connected up by 120 miles of wire and cable. We did the work ourselves—about five of us—with the help of several very keen vacation students who cheerfully sledge-hammered all one summer. It took two years to build and cost about 15,000 pounds, which was cheap even then. We started operating it in July, 1967, although it was several months more before the construction was completely finished.

"I had sole responsibility for operating the telescope and analyzing the data, with supervision from Tony Hewish. We operated it with four beams simultaneously, and scanned all the sky between declinations +50 and −10 once every four days. The output appeared on four 3-track pen recorders, and between them they produced 96 feet of chart paper every day. The charts were analyzed by hand—by me. We decided initially not to computerize the output because until we were familiar with the behavior of our telescope and receivers, we thought it better to inspect the data visually, and because a human can recognize signals of different character whereas it is difficult to program a computer to do so.

"After the first few hundred feet of chart analysis I could recognize the scintillating sources [i.e., the quasars], and I could recognize interference. Six or eight weeks after starting the survey, I became aware that on occasions there was a bit of 'scruff' on the records, which did not look exactly like a scintillating source, and yet did not look exactly like man-made interference either. Furthermore, I realized that this scruff had been seen before on the same part of the records—from the same patch of sky."

Talking it over, Hewish and Bell came to the conclusion that the source of these anomalous signals deserved close attention. They decided to obtain high resolution recordings with a special extra-rapid chart recorder. The radio telescope was only capable of observing sources as they passed overhead in the daily rotation of the sky: she was forced to arrange her schedule around this rotation in order to be present at the telescope whenever the source was detectable. "Towards the end of October, when we had finished doing some special test on [the quasar] 3C273, and when we had at last our full complement of receivers and recorders, I started going out to the observatory each day to make the fast recordings. They were useless. For weeks I recorded nothing but receiver noise. The 'source' had apparently gone.

"Then one day I skipped the observations to go to a lecture, and the next day on my normal recording I saw the scruff had been there. A few days after that, at the end of November '67, I got it on the fast recording. As the chart flowed under the pen, I could see that the signal was a series of pulses, and my suspicion that they were equally spaced was confirmed as soon as I got the chart off the recorder. They were one and one-third seconds apart. I contacted Tony Hewish who was teaching in an undergraduate laboratory in Cambridge, and his first reaction was that they must be man-made. This was a very sensible response in the circumstances, but due to a truly remarkable depth of ignorance I did not see why they could not be from a star. However, he was interested enough to come out to the observatory at transit-time the next day, and fortunately (because pulsars rarely perform to order) the pulses appeared again.

"This is where our problems really started."

It is one thing to discover a series of radio bursts. It is another matter entirely to understand what they are. As things then stood only one thing was clear: that Bell had identified a highly unusual source of radio emission. In the long run it turned out that her discovery marked a minor revolution in astronomy. It was at once the culmination of a thirty-three-year-long story and the beginning of another. But no one knew this at the time.

No one knew what it was that emitted these signals. Was it a star? A galaxy? Or was it something entirely different—an object the likes of which no one had even suspected till then? If it was a star or a galaxy, why were its emissions so unlike those of other stars and galaxies? Was there only one of them or were they common?

It was a long way to the final resolution of these questions.

Initially, it was Hewish, Bell, and their colleagues who sought to understand the pulsations' significance. But they did not get very far. Eventually, without having reached a resolution, they published the announcement of their discovery, and with this announcement the problem passed from their hands to those of the world-wide community of physicists and astronomers as a whole. After this point what had initially been an effort confined to a few became an effort conducted all over the world. It was conducted in scientific papers in the journals; conducted by personal letter and by phone; conducted endlessly in universities as far apart as Moscow, Sydney, London, and New York; in department seminars and over lunch.

How was it done? There is no simple answer to this question short of recounting what actually happened. It is a long story, encompassing the efforts of scientists the world over, and looking back in retrospect it resembles nothing so much as the solution of a gigantic crossword puzzle. It was a matter of piecing together clues.

These clues were contained within the radio pulsations themselves. The pulses were not entirely anonymous. Rather their very structure betrayed the nature of their source. It was the business of the scientists to find more such clues and to weave them together into a coherent picture. It took a little more than a year.

At the outset it seemed to Hewish and Bell that the bursts of radio emission were not astronomical in origin at all. Most likely they merely emanated from some man-made source. They appeared too regular to be natural. The spark plugs of a car, for example, radiate just such regular bursting radio signals with every firing. The signals might also have been produced by an electric clock, or by any of a myriad other possibilities. Arguing against this, however, was the fact that the pulsations appeared in the output of their radio telescope only at a certain time of day; the obvious interpretation was that they were coming from a celestial source and that this source passed over the telescope, and hence was observed, at just this time. It all held together.

But this was not the only possible interpretation. Perhaps the bursts were artificial in nature after all, but only turned on at certain selected times of day. Perhaps it was a radio signal meant to actuate a noon factory whistle, or a ham radio operator of exceedingly regular habits. How to distinguish these two interpretations? How to distinguish the time kept by the sky from the time kept down below?

Actually these two time systems are different. This may not be immediately obvious, for the nighttime sky appears to rotate overhead quite steadily. But although the sky's rotation is regular, it does not occur at the same *rate* as that of the hands of clocks. The easiest way to see this is to fix attention on some particular region of the sky—some obvious constellation, or a bright star—and ask whether it passes overhead on succeeding nights at exactly the same time as determined by clocks.

It does not. Each night this landmark passes overhead a little earlier. Sirius, for instance, the brightest star, passes overhead at midnight in late December, but by spring it does so just after sunset. All through the summer Sirius is up in broad daylight, and hence is invisible, and not until the fall does it become visible again early in the morning. Earthly clocks keep human time: the sky keeps *sidereal* time.

To distinguish the two it was only necessary for Bell to observe the scruff over a moderately long period of time. Did it reappear on the chart recordings at exactly the same time each day? Checking the yards of data that had accumulated over the months, Bell realized that it did not. It was keeping sidereal time.

At about the same time John Pilkington, a third member of Hewish's group, succeeded in measuring the *distance* to the pulsar. He did this by observing the object at a new frequency. Radio telescopes, like ordinary radio receivers, operate at a particular frequency of the electromagnetic spectrum, and up to that point all the observations of the pulsar had been made at one frequency. Pilkington tried another. One changes the frequency at which ordinary radios work simply by adjusting the tuning knob. For a radio telescope the procedure is not easy, but it is straightforward enough for all that. Pilkington decreased the operating frequency of the telescope. But upon doing so he found that the bursts at lower frequencies arrived slightly *after* the higher-frequency bursts.

It immediately occurred to Pilkington that this phenomenon very likely did not originate within the pulsar itself. He felt it more reasonable to assume that the source emitted all frequencies at once. He felt this because he was aware of a peculiarity of the propagation of radio signals through interstellar space, and he realized that this peculiarity could give rise to the very phenomenon he had observed. Radio waves propagate at the speed of light—but only in a vacuum, and interstellar space is filled with a faint residual trace of gas. This gas slows the waves. In fact—and this was Pilkington's point—it slows them selectively. It acts upon the signals according to their frequency. The lower the frequency of the wave, the more it is retarded, and the later it arrives at the Earth.

With this interpretation in hand, it was easy for Pilkington to determine the distance to the pulsar. He was faced with a situation very much like that of a race between two runners, one slightly faster than the other. If the race is a short one—a fifty-yard dash—the faster runner will arrive just barely ahead of the slower; a fraction of a second at most. In a long race, on the other hand—ten miles, for example—the winner might cross the finish line a good five minutes ahead of the runner-up. The longer the distance traveled, the greater will be the gap in time between the arrival of the faster and the slower runners.

All Pilkington had to do was determine how much *sooner* the higher frequency signal arrived than the lower, and then apply the very same logic. He did this. He found that the pulsar was one thousand light years away.

As time passed Hewish and his colleagues found their thoughts turning in a somewhat ominous direction. The pulsations they had found were unnervingly steady. They were *too* steady. Each pulse of radio waves arrived one and one-third seconds after the preceding one. More precisely, they arrived every 1.3373011 seconds, and they maintained this inflexible progression, this perfect regularity, with a constancy seldom found in the natural world. If it was a clock they had discovered, it was a very well-made clock indeed.

Perhaps it was too well-made. Perhaps it was too well-made to be natural.

For after all, when does the natural world ever present us with a phenomenon of perfect regularity? More often than not, nature is chaotic and erratic. Standing alone in the forest one hears a multitude of sounds—but hardly ever a steady, an utterly uniform series of clicks. Is it a woodpecker? More likely it is a hidden clock. By and large, patterns of great order are not the product of natural processes at all. They are the marks of intelligence.

Had Jocelyn Bell discovered an extraterrestrial civilization?

It was a daunting prospect. It was one thing to discover a new and unusual source of radio waves. It was another matter entirely to discover an alien intelligence. Strange as it may sound, there is an element of fear in all scientific discovery. It is compounded of many ingredients. There is the fear of going too far out on a limb, of laying claim to an important discovery when the evidence is not yet complete. There is the fear that one has made some subtle but terrible mistake. And there is the fear of success. There is always the fear—hidden, unstated, lurking in the background—of stumbling upon some discovery so important, so earth-shaking, that it changes the world forever. Hewish, Bell, and their coworkers knew that if they were to claim to have discovered evidence of an extraterrestrial civilization in error, they would be the laughingstock of the scientific community. And if they were right, they would be the authors of a discovery that without exaggeration could be termed one of the most momentous in the history of science.

The signals looked for all the world like pulses of light from a lighthouse. Had Bell discovered some sort of navigational aid, warning interstellar travelers of a celestial menace to shipping? They also looked like pulses of emission from the spark plugs of a car. Had she picked up on the emissions from an unseen spaceship passing in the night? Was she eavesdropping on a celestial dialogue? Or were these signals meant for *us*? Were they intentionally beamed at the Earth by some society anxious to establish contact in an effort to alert us to their presence?

Standing against all this was one important fact. The signals were at the wrong frequency to be artificial. They were at the frequency at which *other* sources of cosmic radio signals emitted most strongly. The quasars, the radio galaxies, supernova remnants, our very galaxy itself—all these natural emitters competed with the pulsars. Other, more quiet bands were available, but the pulsars had not selected them. It would hardly be a rational choice of frequency on the part of their designers. It was as if we were to leave our lighthouses flashing in broad daylight.

It was a plausible argument . . . but not, after all, entirely convincing. For some unknown reason the aliens may have found it useful to employ this frequency anyway. Maybe they liked things that way. We humans, after all, have done more foolish things than that. Hewish decided to perform an alternative test.

He decided to see whether the radio source was located on a planet. Any extraterrestrial civilization would be forced to exist on some planet orbiting about a star. It would be *in motion*—in orbital motion about its sun. And this motion was easy to detect. Hewish used the Doppler effect.

Although it may not be known by name, everyone is familiar with this effect. It operates every time a car drives by with the horn blaring. The abrupt decrease in tone as it passes comes about because the car, initially approaching, has suddenly begun to recede. It is this change in relative motion that is responsible for the change in frequency of the received sound waves.

What is true of sound waves is also true of radio signals from a pulsar. In this case, however, it is not their tone, but the *rate of pulsation* that would be altered. As the planet orbited about its sun it would alternately approach and recede from the Earth. Via the Doppler effect, this continually changing motion relative to us would induce a corresponding regular alteration in the detected rate of pulsation.

Hewish's test was negative. The most careful searches showed the alteration to be absent.

Bell: "Just before Christmas I went to see Tony Hewish about something and walked into a high-level conference about how to present these results. We did not really believe that we had picked up signals from another civilization, but obviously the idea had crossed our minds and we had no proof that it was an entirely natural radio emission. It is an interesting problem—if one thinks one may have detected life elsewhere in the universe, how does one announce the results responsibly? Who does one tell first?

"We did not solve the problem that afternoon, and I went home that evening very cross—here was I trying to get a Ph.D. out of a new technique, and some silly lot of little green men had to choose my aerial and my frequency to communicate with us. However, fortified by some supper, I returned to the lab that evening to do some more chart analysis. Shortly before the lab closed for the night, I was analyzing a recording of a completely different part of the sky, and in amongst a strong heavily modulated signal from [the radio source] Cassiopeia A . . . I thought I saw some scruff. I rapidly checked through previous recordings of that part of the sky, and on occasions there was scruff there. I had to get out of the lab before it locked for the night, knowing that the scruff would transmit in the early hours of the morning.

"So a few hours later I went out to the observatory. It was very cold, and something in our telescope-receiver system suffered drastic loss of gain in cold weather. Of course this was how it was! But by flicking switches, swearing at it, and breathing on it I got it to work properly for five minutes—the right five minutes on the right beam setting. This scruff too then showed itself to be a series of pulses, this time 1.2 seconds apart. I left the recording on Tony's desk and went off, much happier, for Christmas. It was very unlikely that two lots of little green men would both choose the same improbable frequency, and the same time, to try signaling to the same planet Earth."

Too bad.

"Over Christmas, Tony Hewish kindly kept the survey running for me, put fresh paper in the chart recorders, ink in the inkwells, and piled the charts, unanalyzed, on my desk. When I returned after the holiday I could not immediately find him, so I settled down to do some chart analysis. Soon, on the one piece of chart, an hour or so apart in right ascension, I saw *two* more lots of scruff [pulsars number three and four]. It was another fortnight or so before [the second] was confirmed, and soon after that the third and fourth were also. Meanwhile I had checked back through all my previous records (amounting to several miles) to see if there were any other bits of scruff that I had missed. This turned up a number of faintly possible candidates, but nothing as definite as the first four.

"At the end of January, the paper announcing the first pulsar was submitted to *Nature*. A few days before the paper was published, Tony Hewish gave a seminar in Cambridge to announce the results. Every astronomer in Cambridge, so it seemed, came to that seminar, and their interest and excitement gave me a first appreciation of the revolution we had started. In our paper we mentioned that at one stage we had thought the signals might be from another civilization. When the paper was published the press descended, and when they discovered a woman was involved they descended even faster. I had my photograph taken standing on a bank, sitting on a bank, standing on a bank examining bogus records, sitting on a bank examining bogus records; one of them even had me running down the bank waving my arms in the air—look happy, dear, you've just made a Discovery! (Archimedes doesn't know what he missed!) Meanwhile the journalists were asking relevant questions like was I taller than or not quite as tall as Princess Margaret (we have quaint units of measurement in Britain) and how many boyfriends did I have at a time?"

At about this time, Bell's part in the story came to an end. She stopped making observations and handed things over to the next generation of graduate students. She accepted a job in another part of the country in an entirely different field of research. She wrote up her thesis.

The pulsars went in an appendix.

On the ninth of February, 1968, the Cambridge group sent their paper announcing the discovery of pulsars to the British journal *Nature*. Its title was "Observation of a Rapidly Pulsating Radio Source," and it was published in two weeks—an unusually rapid decision on the part of the journal's editors, and one that testified to their sense of the importance of the discovery. That issue of *Nature* carried on its cover the words "possible neutron star."

Within a matter of weeks other research groups were getting into the act. There was a mad scramble to whip together the special equipment required to observe the pulsars. There was a rush to the telescopes. Astronomers who had been promised the use of a telescope for some entirely different project found themselves bombarded by telephone calls from colleagues anxious to use it for pulsar observations. Deals were made. A night on the telescope now was traded for a week six months later. And coincident with this effort, and parallel to it, was the continuing debate on the object responsible for the pulsating emissions.

Over and over again in this debate the same point kept recurring that had occupied Hewish and Bell. It was widely felt that the extreme regularity of pulsar emissions was something worth paying attention to. There was nothing unusual in the fact that they emitted radio waves. Many objects in the sky did this: our own Sun for example, albeit very weakly. Nor was it surprising that the signals fluctuated so rapidly. After all, quasars scintillated all the time—Hewish's telescope had been built to observe these fluctuations. But quasar scintillations were erratic. Before the discovery of pulsars no astronomical source had ever been found to pulse with anything approaching their regularity.

Clearly the pulsars contained within themselves a timekeeping mechanism, some sort of naturally occurring clock controlling their emission. It was on the structure of this clock that most attention focused. The debate on the ultimate nature of pulsars turned out in the end to hinge on just this question, and the way in which it was conducted is an example of the precise, abstract methods of science at its very best. It was a classic argument, beautiful in its sweep and generality, and its final resolution was one of the most telling illustrations I know of the power of abstract reasoning when combined with hard observations. Even now, more than a decade after the fact, it is an example that thrills.

For a variety of reasons it was found that no ordinary star could ever be a pulsar—not the Sun, not any star visible to the naked eye. Only small ultradense stars were capable of emitting such signals, and only two such stellar types existed. The first was the *white dwarf star*. White dwarfs are a fairly common stellar type, although they are so very small—about the size of a planet—that they are difficult to see. Not one is visible to the naked eye.

The second type of ultrasmall star was the neutron star. It had taken a regular train of radio bursts to bring them to the fore.

Three different clock mechanisms were proposed at one point or another during the debate on the nature of pulsars. The first we are all familiar with. It is the passage of the seasons. Winter is followed by spring which gives rise to summer and then fall, and the cycle continues—without end, and with great regularity. This ponderous cycle, this clock, is produced by *the Earth's orbital motion about the Sun.*

It is a far cry from the yearly orbit of the Earth to a series of bursts of radio emission a mere 1.3 seconds apart. How to bridge the gap? The proposal was that a pair of white dwarfs, or neutron stars, could be in orbit about each other. In fact such stellar pairs, or binary stars, are well known to astronomers. A binary system consists of two stars in close proximity to one another orbiting about their common center of mass. Some are visible to the naked eye. The second star in the handle of the Big Dipper is a binary, for example, and its two members, Mizar and Alcor, can be distinguished by those with good eyesight.

It is not so very difficult to imagine how such a pair could emit bursts of radio waves. Figure 1 shows one possibility. They could be generated at the point of contact of the two stars. Surely this is at least possible. After all, the stars are skimming by each other at enormous velocities. Furthermore, as seen from the Earth this emission would appear pulsed. The bulk of the two stars would hide the source from us during most of the orbital period.

Figure 1

There are only two configurations in which the point of contact would be visible to an observer stationed on the Earth: one is illustrated in Figure 1; the other occurs half a revolution later. Within such a model we would receive two brief bursts of radio emission for each orbital cycle of the pair.

A second possibility is illustrated in Figure 2. It relies on the prediction, discussed in Chapter 9, of Einstein's general theory of relativity that the gravitational fields of massive bodies bend the paths of light and radio waves. The bending is large if the bodies are very

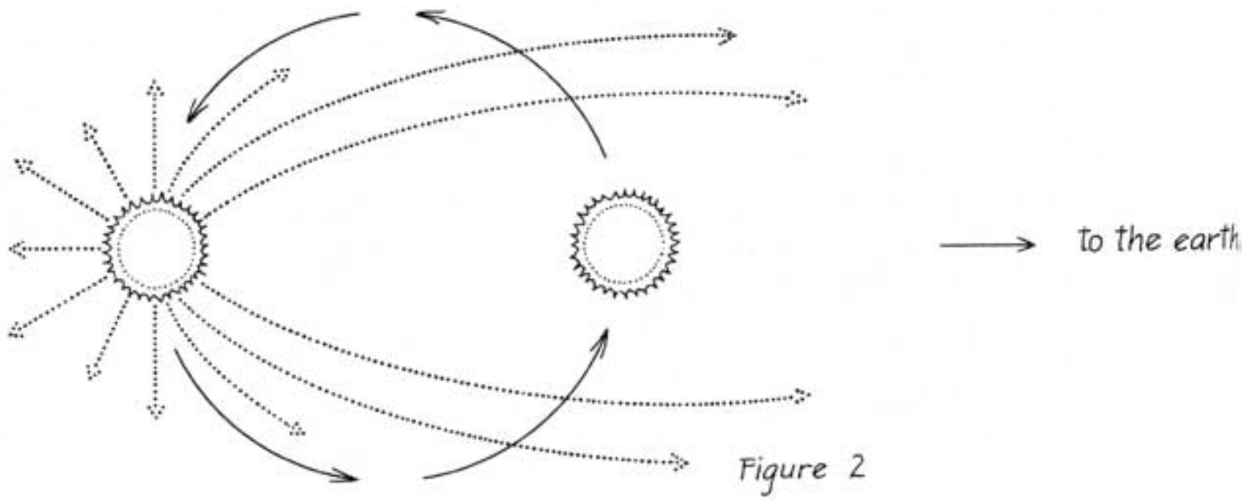

Figure 2

dense: only white dwarfs and neutron stars are sufficiently compact to produce much of an effect. Each member of the binary pair would act as a lens, focusing the signals from the other. If one of the stars were to emit radio waves steadily and in all directions—not a very unusual state of affairs—the lens would bend their path and focus them into a beam. The beam would swing about as the pair revolved; as it swept by the Earth we would receive a pulse.

At least in principle, then, a binary star system is capable of emitting a regular train of radio bursts. Our own earthly astronomical clock ticks quite slowly. Can a much faster clock be imagined that ticks as rapidly as the pulsars?

It is a common feature of all binaries that the closer the two members lie to one another, the more rapidly do they swing about in their orbits. The very same principle is at work in the Solar System. The Earth orbits about the Sun once a year, while Mercury, closer in, completes its swing in 88 days. To construct a rapidly ticking clock we have to construct an exceedingly tight orbit. But there is a limit to the tightness that can be achieved. There could not possibly be a planet so close to the Sun that it orbited about it once a second. The closest an orbit can lie to the Sun is one that just barely skims along its surface, and in such a "minimum" orbit a planet would swing about the Sun once every three hours. Similarly, two ordinary stars can never orbit about each other any more rapidly than once an hour or so.

But white dwarf stars, being smaller than ordinary stars, can get closer to one another. A binary system consisting of two white dwarfs lying quite far apart would have an orbital period of one year—like the Earth. A somewhat tighter system can achieve orbital periods of an hour. But even here the members of the pair are still widely separated. In their closest configuration, in which the two white dwarfs swing about each other barely grazing their surfaces, so rapidly do they move that their "year" can be a mere one second long. And two neutron stars, smaller still, could whirl about each other 1,000 times per second.

So much for the first possible model of the pulsar clock. Orbits are not the only timekeeping mechanism that one finds in nature. In daily experience we have available to us an example of another: the twenty-four-hour cycle of day and night. It is produced *not by the orbit of the Earth but by its spin*. Can a model of pulsar emission be constructed based on rotation?

It is easy to see how such a model could produce pulses. We imagine that the radio emission is confined to a small region on the star—to a spot. Only when this spot is visible from the Earth would its emissions be visible; because the star is rotating it is regularly swinging into and out of view, as Figure 3 illustrates.

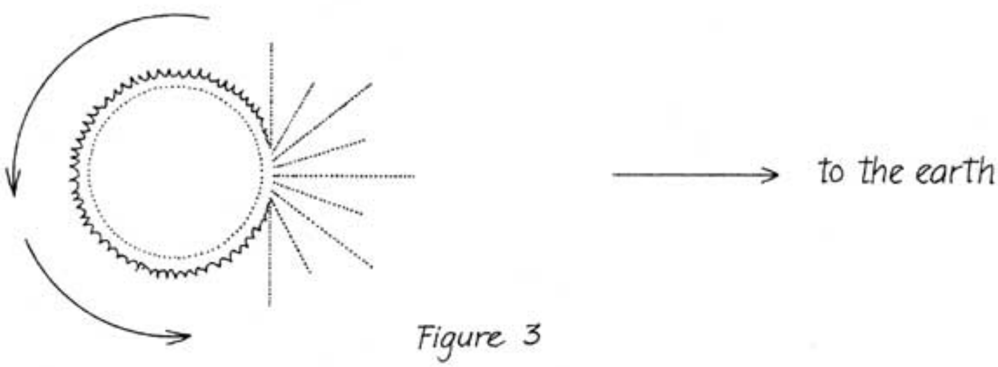

Figure 3

Once again, the extreme rapidity of pulsar bursts puts severe restrictions on the model. It is one thing to spin some everyday object such as a basketball as rapidly as the pulsars tick; it is another matter altogether to spin something as huge as a planet or a star so fast. To illuminate the difficulty consider what would happen if one were to attempt to mimic the pulsars by accelerating the rotation of the *Earth* from its present rate of once every 24 hours to the required rate of once a second.

Do this by the imaginary experiment of mounting giant rocket engines sideways about the equator. On a signal they all commence firing. In response the length of the day grows shorter. The Sun rises and sets with increasing rapidity.

As the process continues things begin to grow lighter. Boulders that once were immovable can now be heaved about with ease. Overweight men and women gaze down upon the bathroom scales with satisfaction. The faster the Earth spins, the less things weigh.

Eventually what was once a matter of some amusement becomes more serious. People no longer can walk, but bound awkwardly down the sidewalks in enormous leaps. Their muscles are too strong for their weights—each person weighs a mere few ounces. A mild gust of wind is enough to send automobiles slithering sideways from their parking places. Stones jostle about alarmingly in the fields. As the rockets keep firing, a critical point is ultimately reached at which the day lasts just 1.4 hours. At this point every object along the equator weighs *nothing*. And as the rate of spin is increased still more, this area of weightlessness extends further north and south away from the equator.

Everything floats away into space. People drift helplessly upward. So do their automobiles. A vast jumble ambles off into the sky—animals, machines. Finally a positive force builds up, and it tugs upward upon everything remaining. Trees are uprooted and hurled into space. Vast chunks of ground tear loose and fly away. The very fabric of the planet is torn apart.

The Earth is ripped apart by rotation. This happens in exactly the same way and for the very same reason that a flywheel tears apart if set spinning too rapidly. Every object in the universe has a natural limit set upon its rate of spin, and if it rotates more rapidly than this limit it is destroyed. The Earth would be destroyed if it were to be spun more rapidly than once every 1.4 hours. The Sun flies apart more easily: it can only be spun once every 2.8 hours. If we are going to explain the pulsars on the basis of some rotating object, we had better be careful to search for one which at the very least is capable of spinning once a second.

As in the case of orbital motion, we are again thrown into the realm of ultrasmall stars. The more compact a star, the more rapidly it can spin. In fact it is gravitation that regulates this effect. The denser a star, the stronger is the force of gravity holding it together, and the more it can withstand the centrifugal effects of rotation. Only white dwarfs and neutron stars are sufficiently compressed to rotate at the required speeds. So strong is gravity on the surface of a white dwarf that a one-hundred-fifty-pound man there would weigh a full 25,000 tons, and on a neutron star gravity is stronger still. White dwarf stars, in consequence, can rotate several times a second; neutron stars, thousands of times a second.

The third and final model of the pulsar timekeeping mechanism is not based upon anything present in our common experience. But it is based on a phenomenon well known to astronomers—so very well known that it is probably fair to say that it was this model that first sprang to most astronomers' minds when the announcement of the discovery of pulsars came out. Certainly the discoverers themselves leaned toward this interpretation in their initial thinking.

It is *the vibration of a star*. Certain stars grow larger and then smaller in a regular progression. Figure 4 diagrams the motion: the star continually oscillates about, expanding and contracting without end, and as it does so it brightens and dims.

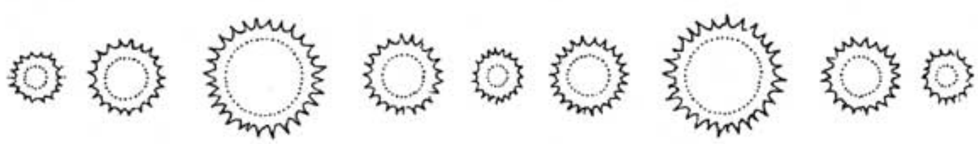

Figure 4

This regular variation in brightness can even be seen with the naked eye in a few cases. For example, the pole star vibrates, and while the vibrations themselves cannot be detected without the use of highly technical equipment, the associated brightening and dimming can. If one observes Polaris with the naked eye quite carefully, one will actually be able to see its changes in brightness.

An important feature of stellar vibrations is that they are quite without end. They do not die out. In this regard the vibrations of a star are very different from those of a bell, for instance, which rings only for a short while after having been struck by a hammer. Neither is the hammer blow required to set the star into vibration. It oscillates for reasons purely internal to itself.

Since vibrating stars vary in visible light, it would be no surprise to find them varying in radio emission as well. The signals might be emitted at some fixed point in the cycle of expansion and contraction of the star; for example, when it reached its minimum size and bounced outward. Alternatively they could be generated at an intermediate stage in the expansion, when the star was rushing outward most rapidly and ramming against its atmosphere, or corona.

Once again, the rapidity of the pulsar clock selects only certain possible candidate stars. It will come as no surprise to the reader to learn that only white dwarfs and neutron stars can vibrate as rapidly as the pulsars. The rate of vibration of a star is determined by the force of gravity upon its surface: the stronger this force, the faster it vibrates. In this regard, a star's rate of oscillation is similar to its maximum rate of rotation: both are fixed by the same physical quantity.

Ordinary stars like the Sun and Polaris have relatively weak gravity: Polaris oscillates once every four days, and the Sun, if for some reason it were to be set vibrating, would do so once every several hours. A white dwarf, on the other hand, could easily vibrate once a second, and in the case of a neutron star we have an embarrassment of riches: such stars, if they vibrate at all, do so thousands of times per second. So if the pulsar clock is provided by the vibration of a star, the star can only be a white dwarf.

The three models of the pulsar clock were proposed in the first few months after the announcement of their discovery, and they were debated fiercely. The pace of research was intense in those months. It was a heady time. A snowstorm, a positive blizzard of scientific papers whirled through the pages of the research journals. Papers were published announcing the discovery of new pulsars. Papers were published announcing the discovery of some new and previously unsuspected aspect of their emissions. Others described in glowing terms various theories of the mechanism responsible for these emissions—all mutually contradictory—and still others, equally contradictory, on the mechanism responsible for their regularity. A researcher would publish the results of his work. Almost before the ink was dry, he would encounter another paper containing some new point that he had neglected to consider. He would dash back to the drawing boards and in due course a new, or revised, paper would appear. It is no exaggeration to say that in the space of a mere few months, more research was done on neutron stars than in all the decades since they had originally been proposed in 1932.

The months rolled by. Confusion reigned, and as late as the fall of 1968, one year after the discovery of pulsars, the situation was still wide open. But then three things happened. Each was of decisive importance, and taken together they resolved the question completely. These three discoveries were made in as many consecutive months—October, November, and December—and almost before people realized what had happened, the problem was solved. By Christmas it was all over but the shouting.

The first was the discovery of the Vela Pulsar. The pulsar was located in the southern hemisphere constellation of Vela and it was very rapid—ten times as rapid as the others. It was almost *too* rapid. Its pulsation rate was nearly too great to be accounted for on the basis of any model involving white dwarf stars. Vela strained these theories to their limits. It forced them into unlikely extremes, into ad hoc assumptions, and it shifted the balance of probabilities toward the hypothesis that pulsars were neutron stars.

But far more important than this, *the pulsar lay within a supernova remnant*. Perhaps the reader will have anticipated this beforehand. A neutron star, born in the fires of a supernova explosion, invariably begins its existence embedded in the explosion's debris. If pulsars were neutron stars, they would have been accompanied by these remnants. But the first pulsars to be discovered were not. Hewish and his group had established conclusively that the original four were located nowhere near any known supernova remnants. The same was true of those discovered subsequently—until the Vela Pulsar came along. But the significance of this fact was unclear. At first glance it appeared to throw the weight of evidence in the direction of the white dwarf hypothesis, but upon more careful consideration it did no such thing—for supernova remnants did not last very long. Like the airborne debris of an ordinary explosion, they were evanescent. Perhaps the fact that the pulsars were not associated with any known supernova remnants merely meant that they were old.

The discovery of the Vela Pulsar established the first clear link between pulsars and neutron stars, and when taken together with the difficulty that white dwarf theories experienced in accounting for this object's rapidity, the evidence became still more compelling. It was beginning to appear that Jocelyn Bell had discovered the first neutron star.

Almost before the astronomical community had time to assimilate Vela's significance the second of the three seminal discoveries of 1968 was made—and if the first had been important, this was crucial. It broke the back of the problem. It was the discovery of the Crab Pulsar. This pulsar too was embedded in a supernova remnant, but its true significance lay elsewhere. It was in the pulsar's extreme rapidity. The Crab emitted at the unheard-of rate of 30 bursts per second, and if the white dwarf theories had been strained by Vela, they were annihilated by the Crab. This pulsar was too fast to allow the slightest ambiguity; its 30 bursts per second sounded the death knell for every idea involving white dwarf stars. With this one stroke, entire groups of theories tumbled into oblivion.

Only two possibilities then remained: rotation and orbital motion of neutron stars. How to decide between them?

The decision was made by the last of the three discoveries of 1968, but before recounting this discovery it will pay us to pause. There was an anomaly, a peculiarity in the facts of the matter as they stood in November of that year, and the anomaly was suggestive. Most of the pulsars in the sky bore no visible relation to supernova remnants. Only two, the Crab and Vela, were situated within such remnants. And these were the two fastest pulsars.

Were these facts related?

Why should it be that out of all the pulsars in the sky, only the two fastest occupied these remnants? By this stage it had become clear that pulsars were neutron stars, and that their births were marked by one of the most violent and cataclysmic events known to science: the supernova explosion of a star. The slow pulsars were no longer accompanied by the remnants of these explosions. They had outlived them. It was only the faster ones that were still surrounded by the debris of their birth.

It was almost as if the faster pulsars were the younger ones.

As indeed they were. A mere one month after the discovery of the Crab Pulsar, the group that found it observed it again—and observed that it was ticking more slowly. The Crab Pulsar was slowing down.

All at once the first inkling of an enormous vision rushed over the scientific community. In an instant the vast sweep of pulsar evolution was laid bare. A pulsar began its existence wrapped in the fires of the supernova explosion of a star. It began pulsing with great rapidity—far more rapidly than any pulsar known to us now. As the ages passed—thousands of years, millions of years—the pulsar steadily slowed, and as it slowed, its enveloping supernova remnant expanded. After one thousand years the pulsar had slowed to 30 pulsations per second—it had become the Crab Pulsar—and its surrounding remnant expanded ten light years—it had become the Crab Nebula. After 20,000 years it had evolved into the Velva Pulsar: pulsing more slowly, embedded in a nebula far more extended and tenuous. Ultimately, as the millennia rolled by and the remnant entirely dissipated into the vastness of interstellar space, the pulsar was stripped of the signs of its birth. Now it was pulsing a mere once a second.

The discovery of pulsar deceleration also nailed down their underlying nature, for of the two remaining models of the pulsar clock, only one was even capable of slowing down. This model was rotation. Spinning objects could easily decrease their rate of spin, and ultimately come to rest. Spinning tops did it all the time. But as for orbital motion just the opposite was true. These clocks could not slow down. Indeed, they sped up.

They sped up because of the emission of gravitational waves. Any orbiting object emits such waves. The Earth does so right now in its passage about the Sun, and so do the other planets of the Solar System and every binary star. The consequence of the emission of this gravitational radiation is that the orbiting object slowly spirals inward. Right now the Earth is microscopically drifting toward the Sun—and the closer it gets, the shorter is the year.

Within the Solar System this process is exceedingly weak. It is so minute that it has not the slightest practical significance. Over the entire history of the existence of our planet—more than 4 billion years—it has literally moved the Earth inward not even a hair's breadth and the year has not shortened by a second. But because they were orbiting so rapidly, this emission would be stronger in the case of the postulated binary system containing two neutron stars. Since they emitted more strongly, they would spiral in toward each other more rapidly—and the pulsar clock would speed up quite noticeably.

With this last small step the debate on the nature of the pulsars came to an end. The discovery of pulsar deceleration ruled out the binary star model, and by elimination only one model remained. Pulsars were *rotating neutron stars*.

So it was that neutron stars were discovered, and the ideas of Baade, Zwicky, and Landau borne out. They were borne out a full 33 years after these scientists had proposed them, and in ways they could not possibly have foreseen. It happened by accident, when a young woman discovered the first pulsar. Or perhaps it had happened earlier, when an eminent astronomer decided to build a new kind of radio telescope. Or perhaps it did not happen until a full year had passed and the Crab Pulsar and its deceleration was found, and their significance was forged in the hard fires of an international debate. It happened, at any rate.

In some ways it was an unsatisfactory discovery. For after all, what direct evidence have we found for the existence of neutron stars? The entire story is based upon a rapid train of radio pulsations whose rate is gradually diminishing. It is a long way from this to the actual observation of a tiny ball of neutronic matter lost in the vastness of space. It has been a purely negative argument that we have recounted. People drew up a list of possible candidates and eliminated all but one. At its heart the story of the discovery of neutron stars can be reduced to a single question: what else could the pulsars be?

There is only one reply—nothing. Nevertheless even now, more than a decade after the fact, we have *still* not succeeded in directly observing a neutron star. They are too small to be seen. If it were not for their strange ability to emit radio pulses, they never would have been found at all.

The discovery of neutron stars raised more questions than it answered, and showed them to be far stranger beasts than anyone had thought. Nothing in the original ideas of Baade, Zwicky, and Landau gave the slightest indication that they would behave in such a way. After all, the Earth rotates, and the Sun, but they do not emit pulses. Neutron stars, alone among every class of star in the sky, have this uncanny ability. This arose from their emission of radio signals from a small portion of their surfaces, but no one understood how they did this. No one knew how they acted for all the world like cosmic lighthouses. And no one knew how they slowed down.

Hewish, Bell, *et al.*, *"Observation of a Rapidly Pulsating Radio Source,"* *Nature* vol 217, p.709 (24 Feb. 1968).

Observation of a Rapidly Pulsating Radio Source

by

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Unusual signals from pulsating radio sources have been recorded at the Mullard Radio Astronomy Observatory. The radiation seems to come from local objects within the galaxy, and may be associated with oscillations of white dwarf or neutron stars.

In July 1967, a large radio telescope operating at a frequency of 81·5 MHz was brought into use at the Mullard Radio Astronomy Observatory. This instrument was designed to investigate the angular structure of compact radio sources by observing the scintillation caused by the irregular structure of the interplanetary medium[1]. The initial survey includes the whole sky in the declination range $-08° < \delta < 44°$ and this area is scanned once a week. A large fraction of the sky is thus under regular surveillance. Soon after the instrument was brought into operation it was noticed that signals which appeared at first to be weak sporadic interference were repeatedly observed at a fixed declination and right ascension; this result showed that the source could not be terrestrial in origin.

Systematic investigations were started in November and high speed records showed that the signals, when present, consisted of a series of pulses each lasting $\sim 0·3$ s and with a repetition period of about 1·337 s which was soon found to be maintained with extreme accuracy. Further observations have shown that the true period is constant to better than 1 part in 10^7 although there is a systematic variation which can be ascribed to the orbital motion of the Earth. The impulsive nature of the recorded signals is caused by the periodic passage of a signal of descending frequency through the 1 MHz pass band of the receiver.

The remarkable nature of these signals at first suggested an origin in terms of man-made transmissions which might arise from deep space probes, planetary radar or the reflexion of terrestrial signals from the Moon. None of these interpretations can, however, be accepted because the absence of any parallax shows that the source lies far outside the solar system. A preliminary search for further pulsating sources has already revealed the presence of three others having remarkably similar properties which suggests that this type of source may be relatively common at a low flux density. A tentative explanation of these unusual sources in terms of the stable oscillations of white dwarf or neutron stars is proposed.

Position and Flux Density

The aerial consists of a rectangular array containing 2,048 full-wave dipoles arranged in sixteen rows of 128 elements. Each row is 470 m long in an E.–W. direction and the N.–S. extent of the array is 45 m. Phase-scanning is employed to direct the reception pattern in declination and four receivers are used so that four different declinations may be observed simultaneously. Phase-switching receivers are employed and the two halves of the aerial are combined as an E.–W. interferometer. Each row of dipole elements is backed by a tilted reflecting screen so that maximum sensitivity is obtained at a declination of approximately $+30°$, the overall sensitivity being reduced by more than one-half when the beam is scanned to declinations above $+90°$ and below $-5°$. The beamwidth of the array to half intensity is about $\pm \frac{1}{2}°$ in right ascension and $\pm 3°$ in declination; the phasing arrangement is designed to produce beams at roughly 3° intervals in declination. The receivers have a bandwidth of 1 MHz centred at a frequency of 81·5 MHz and routine recordings are made with a time constant of 0·1 s; the r.m.s. noise fluctuations correspond to a flux density of $0·5 \times 10^{-26}$ W m^{-2} Hz^{-1}. For detailed studies of the pulsating source a time constant of 0·05 s was usually employed and the signals were displayed on a multi-channel 'Rapidgraph' pen recorder with a time constant of 0·03 s. Accurate timing of the pulses was achieved by recording second pips derived from the *MSF* Rugby time transmissions.

A record obtained when the pulsating source was un-

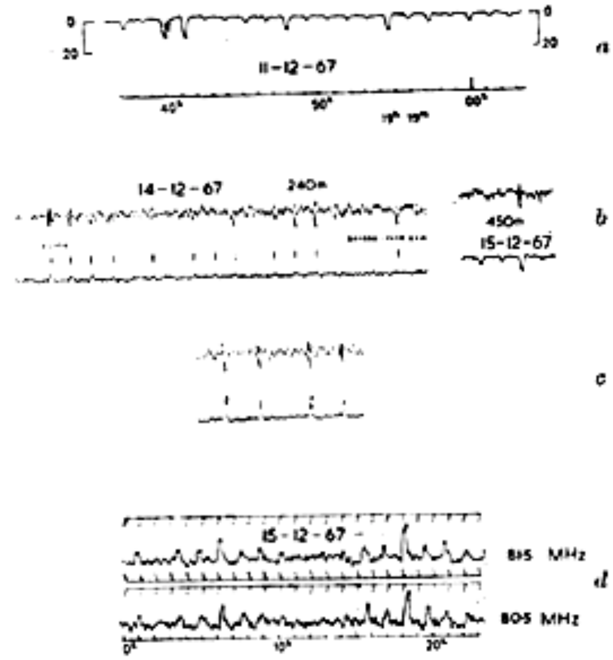

Fig. 1. *a*, A record of the pulsating radio source in strong signal conditions (receiver time constant 0·1 s). Full scale deflexion corresponds to 20×10^{-26} W m^{-2} Hz^{-1}. *b*, Upper trace: records obtained with additional paths (240 m and 450 m) in one side of the interferometer. Lower trace: normal interferometer records. (The pulses are small for $l = 240$ m because they occurred near a null in the interference pattern; this modifies the phase but not the amplitude of the oscillatory response on the upper trace.) *c*, Simulated pulses obtained using a signal generator. *d*, Simultaneous reception of pulses using identical receivers tuned to different frequencies. Pulses at the lower frequency are delayed by about 0·2 s.

usually strong is shown in Fig. 1*a*. This clearly displays the regular periodicity and also the characteristic irregular variation of pulse amplitude. On this occasion the largest pulses approached a peak flux density (averaged over the 1 MHz pass band) of 20×10^{-26} W m^{-2} Hz^{-1}, although the mean flux density integrated over one minute only amounted to approximately $1{\cdot}0 \times 10^{-26}$ W m^{-2} Hz^{-1}. On a more typical occasion the integrated flux density would be several times smaller than this value. It is therefore not surprising that the source has not been detected in the past, for the integrated flux density falls well below the limit of previous surveys at metre wavelengths.

The position of the source in right ascension is readily obtained from an accurate measurement of the "crossover" points of the interference pattern on those occasions when the pulses were strong throughout an interval embracing such a point. The collimation error of the instrument was determined from a similar measurement on the neighbouring source 3*C* 409 which transits about 52 min later. On the routine recordings which first revealed the source the reading accuracy was only ± 10 s and the earliest record suitable for position measurement was obtained on August 13, 1967. This and all subsequent measurements agree within the error limits. The position in declination is not so well determined and relies on the relative amplitudes of the signals obtained when the reception pattern is centred on declinations of 20°, 23° and 26°. Combining the measurements yields a position

$$\alpha_{1950} = 19\text{h}\ 19\text{m}\ 38\text{s} \pm 3\text{s}$$

$$\delta_{1950} = 22^\circ\ 00' \pm 30'$$

As discussed here, the measurement of the Doppler shift in the observed frequency of the pulses due to the Earth's orbital motion provides an alternative estimate of the declination. Observations throughout one year should yield an accuracy of $\pm 1'$. The value currently attained from observations during December–January is $\delta = 21^\circ\ 58' \pm 30'$, a figure consistent with the previous measurement.

Time Variations

It was mentioned earlier that the signals vary considerably in strength from day to day and, typically, they are only present for about 1 min, which may occur quite randomly within the 4 min interval permitted by the reception pattern. In addition, as shown in Fig. 1*a*, the pulse amplitude may vary considerably on a time-scale of seconds. The pulse to pulse variations may possibly be explained in terms of interplanetary scintillation[1], but this cannot account for the minute to minute variation of mean pulse amplitude. Continuous observations over periods of 30 min have been made by tracking the source with an E.–W. phased array in a 470 m × 20 m reflector normally used for a lunar occultation programme. The peak pulse amplitude averaged over ten successive pulses for a period of 30 min is shown in Fig. 2*a*. This plot suggests the possibility of periodicities of a few minutes duration, but a correlation analysis yields no significant result. If the signals were linearly polarized, Faraday rotation in the ionosphere might cause the random variations, but the form of the curve does not seem compatible with this mechanism. The day to day variations since the source was first detected are shown in Fig. 2*b*. In this analysis the daily value plotted is the peak flux density of the greatest pulse. Again the variation from day to day is irregular and no systematic changes are clearly evident, although there is a suggestion that the source was significantly weaker during October to November. It therefore appears that, despite the regular occurrence of the pulses, the magnitude of the power emitted exhibits variations over long and short periods.

Instantaneous Bandwidth and Frequency Drift

Two different experiments have shown that the pulses are caused by a narrow-band signal of descending frequency sweeping through the 1 MHz band of the receiver. In the first, two identical receivers were used, tuned to frequencies of 80·5 MHz and 81·5 MHz. Fig. 1*d*, which illustrates a record made with this system, shows that the lower frequency pulses are delayed by about 0·2 s. This corresponds to a frequency drift of ~ -5 MHz s^{-1}. In the second method a time delay was introduced into the signals reaching the receiver from one-half of the aerial by incorporating an extra cable of known length l. This cable introduces a phase shift proportional to frequency so that, for a signal the coherence length of which exceeds l, the output of the receiver will oscillate with period

$$t_0 = \frac{c}{l}\left(\frac{d\nu}{dt}\right)^{-1}$$

where $d\nu/dt$ is the rate of change of signal frequency. Records obtained with $l = 240$ m and 450 m are shown in Fig. 1*b* together with a simultaneous record of the pulses derived from a separate phase-switching receiver operating with equal cables in the usual fashion. Also shown, in Fig. 1*c*, is a simulated record obtained with exactly the same arrangement but using a signal generator, instead of the source, to provide the swept frequency. For observation with $l > 450$ m the periodic oscillations were slowed down to a low frequency by an additional phase shifting device in order to prevent severe attenuation of the output signal by the time constant of the receiver. The rate of change of signal frequency has been deduced from the additional phase shift required and is $d\nu/dt = -4{\cdot}9 \pm 0{\cdot}5$ MHz s^{-1}. The direction of the frequency drift can be obtained from the phase of the oscillation on the record and is found to be from high to low frequency in agreement with the first result.

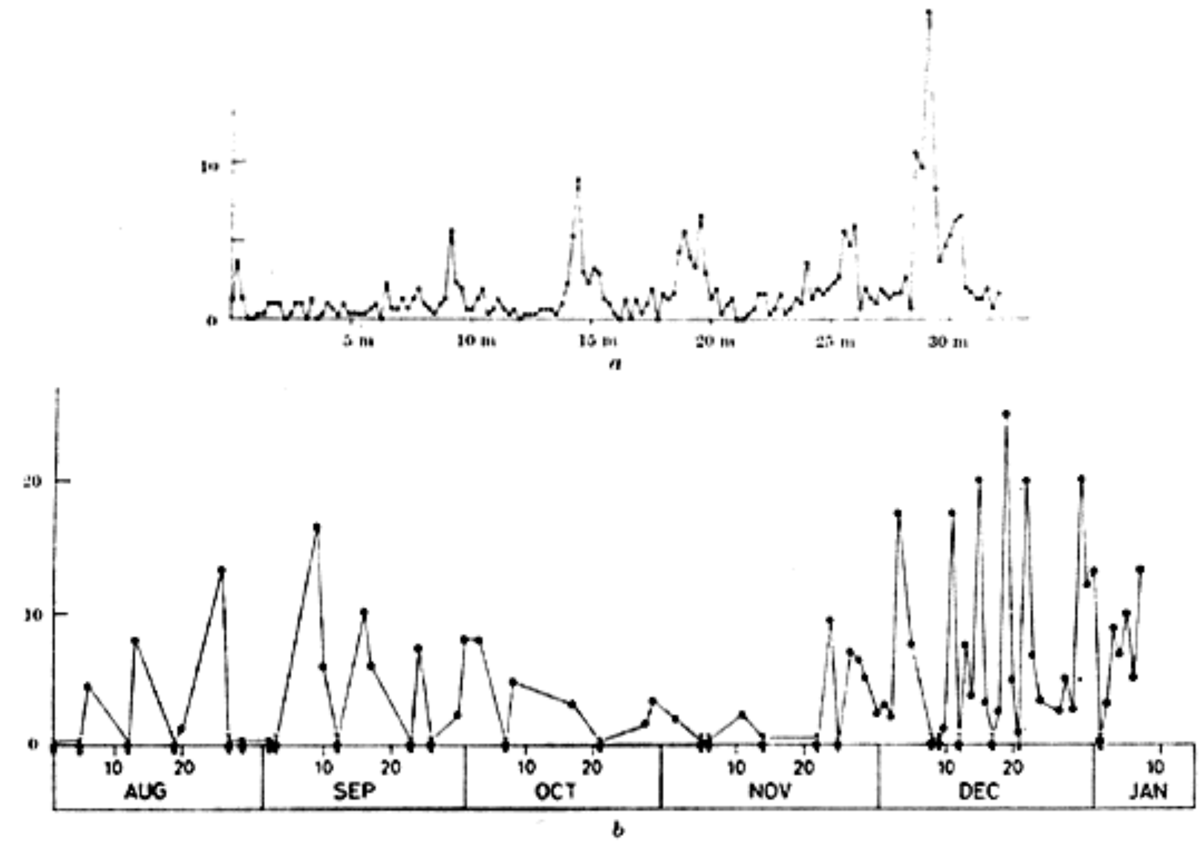

Fig. 2. *a*, The time variation of the smoothed (over ten pulses) pulse amplitude. *b*, Daily variation of peak pulse amplitude. (Ordinates are in units of $W\ m^{-2}\ Hz^{-1} \times 10^{-26}$.)

The instantaneous bandwidth of the signal may also be obtained from records of the type shown in Fig. 1*b* because the oscillatory response as a function of delay is a measure of the autocorrelation function, and hence of the Fourier transform, of the power spectrum of the radiation. The results of the measurements are displayed in Fig. 3 from which the instantaneous bandwidth of the signal to exp (-1), assuming a Gaussian energy spectrum, is estimated to be 80 ± 20 kHz.

Pulse Recurrence Frequency and Doppler Shift

By displaying the pulses and time pips from *MSF* Rugby on the same record the leading edge of a pulse of reasonable size may be timed to an accuracy of about

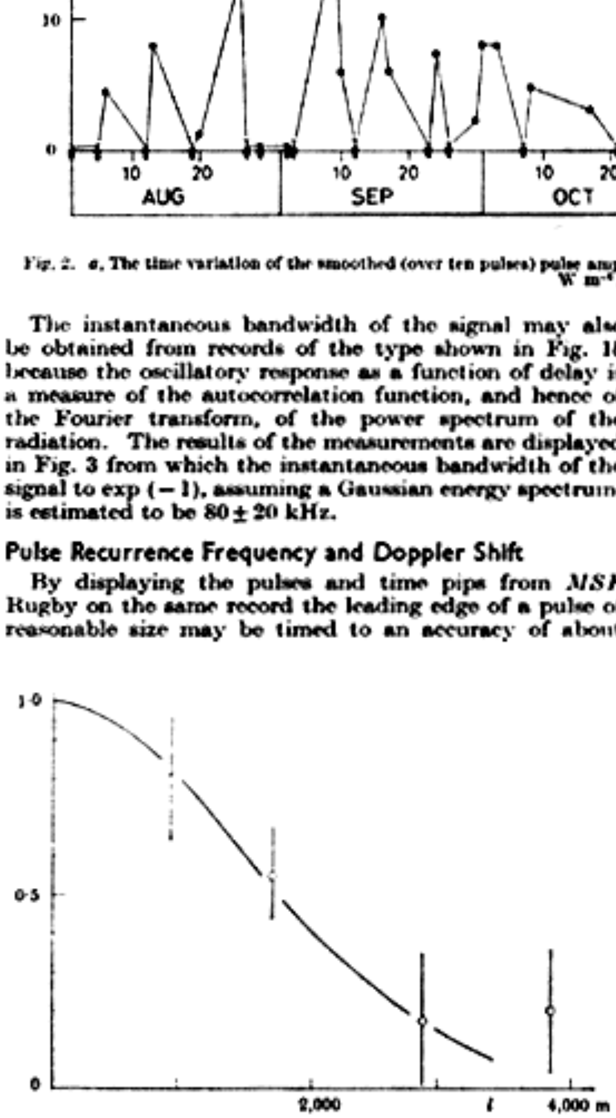

Fig. 3. The response as a function of added path in one side of the interferometer.

0·1 s. Observations over a period of 6 h taken with the tracking system mentioned earlier gave the period between pulses as $P_{obs} = 1{\cdot}33733 \pm 0{\cdot}00001$ s. This represents a mean value centred on December 18, 1967, at 14 h 18 m UT. A study of the systematic shift in the frequency of the pulses was obtained from daily measurements of the time interval T between a standard time and the pulse immediately following it as shown in Fig. 4. The standard time was chosen to be 14 h 01 m 00 s UT on December 11 (corresponding to the centre of the reception pattern) and subsequent standard times were at intervals of 23 h 56 m 04 s (approximately one sidereal day). A plot of the variation of T from day to day is shown in Fig. 4. A constant pulse recurrence frequency would show a linear increase or decrease in T if care was taken to add or subtract one period where necessary. The observations, however, show a marked curvature in the sense of a steadily increasing frequency. If we assume a Doppler shift due to the Earth alone, then the number of pulses received per day is given by

$$N = N_0 \left(1 + \frac{v}{c} \cos \varphi \sin \frac{2\pi n}{366{\cdot}25}\right)$$

where N_0 is the number of pulses emitted per day at the source, v the orbital velocity of the Earth, φ the ecliptic latitude of the source and n an arbitrary day number obtained by putting $n = 0$ on January 17, 1968, when the Earth has zero velocity along the line of sight to the source. This relation is approximate since it assumes a circular orbit for the Earth and the origin $n = 0$ is not exact, but it serves to show that the increase of N observed can be explained by the Earth's motion alone within the accuracy currently attainable. For this purpose it is convenient to estimate the values of n for which $\delta T/\delta n = 0$, corresponding to an exactly integral value of N. These occur at $n_1 = 15{\cdot}8 \pm 0{\cdot}1$ and $n_2 = 28{\cdot}7 \pm 0{\cdot}1$, and since N

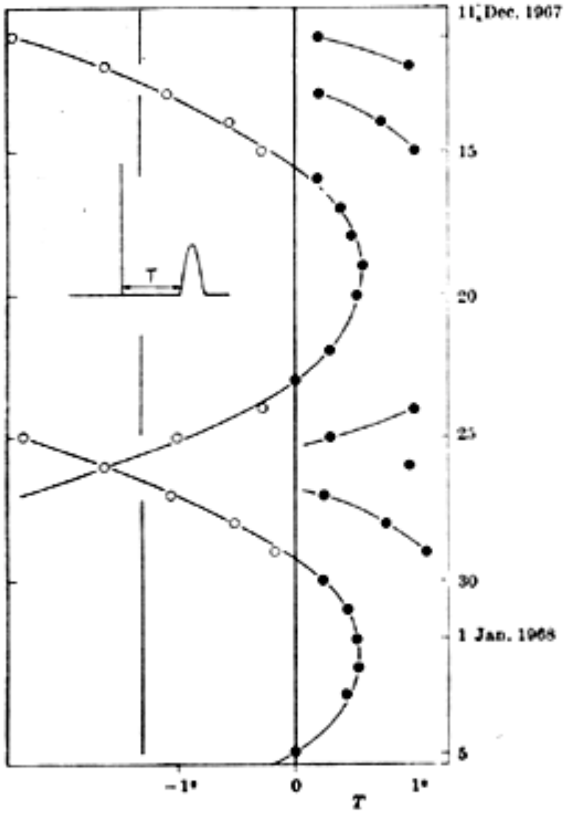

Fig. 4. The day to day variation of pulse arrival time.

is increased by exactly one pulse between these dates we have

$$1 = \frac{N_0 v}{c} \cos \varphi \left[\sin \frac{2\pi n_2}{366{\cdot}25} - \sin \frac{2\pi n_1}{366{\cdot}25} \right]$$

This yields $\varphi = 43° \; 36' \pm 30'$ which corresponds to a declination of $21° \; 58' \pm 30'$, a value consistent with the declination obtained directly. The true periodicity of the source, making allowance for the Doppler shift and using the integral condition to refine the calculation, is then

$$P_0 = 1{\cdot}3372795 \pm 0{\cdot}0000020 \text{ s}$$

By continuing observations of the time of occurrence of the pulses for a year it should be possible to establish the constancy of N_0 to about 1 part in 3×10^8. If N_0 is indeed constant, then the declination of the source may be estimated to an accuracy of $\pm 1'$; this result will not be affected by ionospheric refraction.

It is also interesting to note the possibility of detecting a variable Doppler shift caused by the motion of the source itself. Such an effect might arise if the source formed one component of a binary system, or if the signals were associated with a planet in orbit about some parent star. For the present, the systematic increase of N is regular to about 1 part in 2×10^7 so that there is no evidence for an additional orbital motion comparable with that of the Earth.

The Nature of the Radio Source

The lack of any parallax greater than about 2′ places the source at a distance exceeding 10^3 A.U. The energy emitted by the source during a single pulse, integrated over 1 MHz at 81·5 MHz, therefore reaches a value which must exceed 10^{17} erg if the source radiates isotropically. It is also possible to derive an upper limit to the physical dimension of the source. The small instantaneous bandwidth of the signal (80 kHz) and the rate of sweep (−4·9 MHz s^{-1}) show that the duration of the emission at any given frequency does not exceed 0·016 s. The source size therefore cannot exceed $4{\cdot}8 \times 10^3$ km.

An upper limit to the distance of the source may be derived from the observed rate of frequency sweep since impulsive radiation, whatever its origin, will be dispersed during its passage through the ionized hydrogen in interstellar space. For a uniform plasma the frequency drift caused by dispersion is given by

$$\frac{d\nu}{dt} = -\frac{c}{L} \frac{\nu^3}{\nu_p^{\,2}}$$

where L is the path and ν_p the plasma frequency. Assuming a mean density of 0·2 electron cm^{-3} the observed frequency drift (−4·9 MHz s^{-1}) corresponds to $L \sim 65$ parsec. Some frequency dispersion may, of course, arise in the source itself; in this case the dispersion in the interstellar medium must be smaller so that the value of L is an upper limit. While the interstellar electron density in the vicinity of the Sun is not well known, this result is important in showing that the pulsating radio sources so far detected must be local objects on a galactic distance scale.

The positional accuracy so far obtained does not permit any serious attempt at optical identification. The search area, which lies close to the galactic plane, includes two twelfth magnitude stars and a large number of weaker objects. In the absence of further data, only the most tentative suggestion to account for these remarkable sources can be made.

The most significant feature to be accounted for is the extreme regularity of the pulses. This suggests an origin in terms of the pulsation of an entire star, rather than some more localized disturbance in a stellar atmosphere. In this connexion it is interesting to note that it has already been suggested[2,3] that the radial pulsation of neutron stars may play an important part in the history of supernovae and supernova remnants.

A discussion of the normal modes of radial pulsation of compact stars has recently been given by Meltzer and Thorne[4], who calculated the periods for stars with central densities in the range 10^5 to 10^{19} g cm^{-3}. Fig. 4 of their paper indicates two possibilities which might account for the observed periods of the order 1 s. At a density of 10^7 g cm^{-3}, corresponding to a white dwarf star, the fundamental mode reaches a minimum period of about 8 s; at a slightly higher density the period increases again as the system tends towards gravitational collapse to a neutron star. While the fundamental period is not small enough to account for the observations the higher order modes have periods of the correct order of magnitude. If this model is adopted it is difficult to understand why the fundamental period is not dominant; such a period would have readily been detected in the present observations and its absence cannot be ascribed to observational effects. The alternative possibility occurs at a density of 10^{13} g cm^{-3}, corresponding to a neutron star; at this density the fundamental has a period of about 1 s, while for densities in excess of 10^{13} g cm^{-3} the period rapidly decreases to about 10^{-3} s.

If the radiation is to be associated with the radial pulsation of a white dwarf or neutron star there seem to be several mechanisms which could account for the radio emission. It has been suggested that radial pulsation would generate hydromagnetic shock fronts at the stellar surface which might be accompanied by bursts of X-rays and energetic electrons[2,3]. The radiation might then be likened to radio bursts from a solar flare occurring over the entire star during each cycle of the oscillation. Such a model would be in fair agreement with the upper limit of $\sim 5 \times 10^3$ km for the dimension of the source, which compares with the mean value of 9×10^3 km quoted for white dwarf stars by Greenstein[5]. The energy requirement for this model may be roughly estimated by noting that the total energy emitted in a 1 MHz band by a type III solar burst would produce a radio flux of the right is assumed that the radio energy may be related to the total flare energy ($\sim 10^{34}$ erg)[5] in the same manner as for a solar flare and supposing that each pulse corresponds to one flare, the required energy would be $\sim 10^{39}$ erg yr^{-1}; at a distance of 65 pc the corresponding value would be $\sim 10^{47}$ erg yr^{-1}. It has been estimated that a neutron star may contain $\sim 10^{51}$ erg in vibrational modes so the energy requirement does not appear unreasonable, although other damping mechanisms are likely to be important when considering the lifetime of the source[4].

The swept frequency characteristic of the radiation is reminiscent of type II and type III solar bursts, but it seems unlikely that it is caused in the same way. For a white dwarf or neutron star the scale height of any atmosphere is small and a travelling disturbance would be expected to produce a much faster frequency drift than is actually observed. As has been mentioned, a more likely possibility is that the impulsive radiation suffers dispersion during its passage through the interstellar medium.

More observational evidence is clearly needed in order to gain a better understanding of this strange new class of radio source. If the suggested origin of the radiation is confirmed further study may be expected to throw valuable light on the behaviour of compact stars and also on the properties of matter at high density.

We thank Professor Sir Martin Ryle, Dr J. E. Baldwin, Dr P. A. G. Scheuer and Dr J. R. Shakeshaft for helpful discussions and the Science Research Council who financed this work. One of us (S. J. B.) thanks the Ministry of Education of Northern Ireland and another (R. A. C.) the SRC for a maintenance award; J. D. H. P. thanks ICI for a research fellowship.

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"Discovery of Optical Signals from Pulsar NP 0532". **W.J. Cocke, M.J. Disney, and D.J. Taylor. Nature, February 8, 1969, volume 221, p. 525.**

Discovery of Optical Signals from Pulsar *NP* 0532

by

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Strong light flashes have been detected from the fast pulsar in the Crab Nebula.

We wish to report the discovery on January 16, 1969, $03^{h}\ 30^{m}$ UT, of strong optical pulses from the pulsating radio source *NP* 0532 in the Crab Nebula. The radio pulses were first detected by Staelin and Reifenstein[1]. The optical pulses were observed by us to have a geocentric period of 0·033095 s, which agrees well with the projected heliocentric radio period[2].

The pulses were observed on January 16, 17, 18 and 20 (UT) with the Steward Observatory 36 inch $f/5$ reflecting telescope and a 1P21 photomultiplier. They were observed in real time on the cathode ray tube of a 400 channel computer of average transients (CAT). The CAT adds successive cycles of the pulsation waveform in phase.

Our magnitude analysis of the pulses, which we present in more detail later, shows that the time-averaged optical flux of the pulses alone would be equivalent to a star of apparent visual magnitude + 17·7. Because the maximum size of the object ought to be at most comparable with the distance travelled by light in one period ($\approx 10^{9}$ cm), the source of the pulsations should be apparent as a point image on a high-resolution photograph of the Crab Nebula.

By sweeping a diaphragm of 22 arc s diameter around the central region of the Crab Nebula, we determined that the optical pulses came from a point 5 (± 5) arc s north and 4 (± 5) arc s east of the south preceding component of the central double star in the Crab Nebula. The double star has a separation of 4 arc s, and thus the north following component is nearer the centre of the error circle (see Fig. 1). The only star-like objects appearing in our position error circle are the two components of the central double, both of approximate visual magnitude $V \approx +16$. The north following star, however, is generally regarded[3] as not being associated with the nebula, whereas the south preceding star has roughly the same proper motion as the nebula itself[3,4]. Thus we tentatively identify the source of the optical pulsations as the south preceding component located[3] at $\alpha(1950) = 5^{h}\ 31^{m}\ 31{\cdot}5^{s}$ and $\delta(1950) = +21°\ 58'\ 55''$.

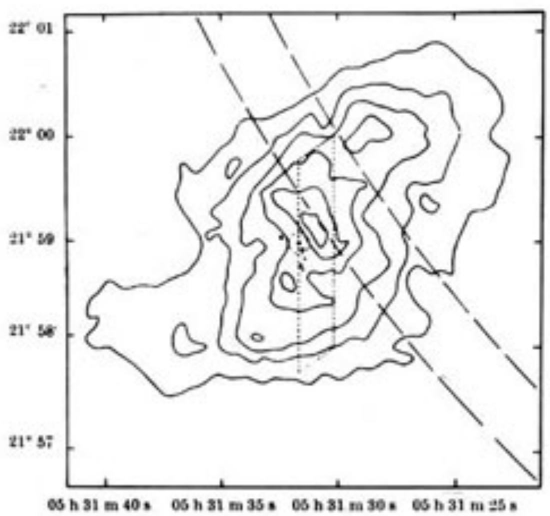

Fig. 1. (Adopted from Gower[10].) Positions of objects in the Crab Nebula superimposed on optical isophotes due to Woltjer[11]—the X-ray source (dashed arcs), the anomalous radio source (parallelogram) and star-like images[11] near the central double star (inside circle). The circle represents the probable location of the optical pulse source.

Fig. 2 shows the first pulse observed by us on the CAT screen, this particular pulse being a superposition of roughly 5,000 pulses taken through the 22 arc s diaphragm. Fig. 3 depicts a superposition of 300 pulses taken through a 5 arc s diaphragm. Note the improved pulse height relative to the background. The secondary interpulse is usually present and is somewhat broader than the primary pulse. Occasionally the relative heights of the two pulses seem to change, as shown in Fig. 4. The time scale for gross changes in the relative pulse shapes seems to be about 2 h.

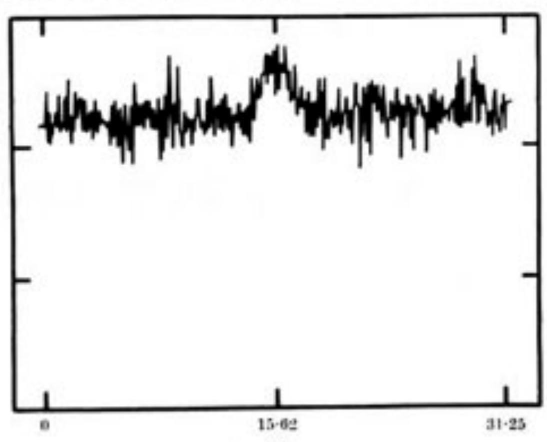

Fig. 2. The first pulse observed on the CAT screen, January 16, 1969, $03^{h}\ 30^{m}$ UT, with 22 arc s diaphragm and summing 5,000 periods. The amplitude scale is arbitrary. The last 2 ms of the pulse period are not stored by the CAT.

Our best observation (Fig. 3) shows a rise time (10 per cent–90 per cent) for the main pulse of 1·6 ms, a fall time of 1·2 ms and a half width of 1·4 ms. The interpulse trails the main pulse by 14·0 ms, and the half width of the interpulse is 3 ms.

The *UBV* magnitude observations were made on January 18, 1969, $08^{h}\ 00^{m}$ UT. The calculated values are based on previously measured mean values for atmospheric extinction and transformation to the *UBV* system. The *V* magnitude of the main pulse smeared out over a complete period is $V = +18{\cdot}2$. For both main and interpulse together, $V = +17{\cdot}7$. The peak brilliance of the main pulse is $V = +15{\cdot}1$. The peak amplitude of the interpulse is 30 per cent of the peak main pulse. The observed colours of the main pulse are $U\text{–}B = -0{\cdot}8$.

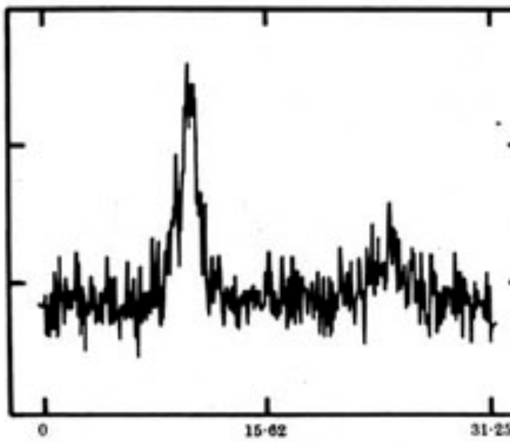

Fig. 3. A pulse taken through the 5 arc s diaphragm on January 20, 1969, 06h 00m UT, summing 300 periods.

$B-V = +0.8$. If one assumes the secondary pulse to have the same colours, the total optical pulse energy flux incident on the Earth comes out to be 1.0×10^{-13} erg cm^{-2} s^{-1}. If this is corrected for interstellar reddening and absorption[3,4] over the 2 kpc distance of the Crab Nebula[3,4], the corrected flux would be 8×10^{-12} erg cm^{-2} s^{-1}. The corrected colours are $U-B = -1.3$, $B-V = +0.1$. In Fig. 5 we have plotted the corrected pulse colours on a $U-B$, $B-V$ diagram, together with various stellar and quasi-stellar objects. Note that the pulse colours are extraordinarily blue, suggesting large ultraviolet and X-ray pulse fluxes.

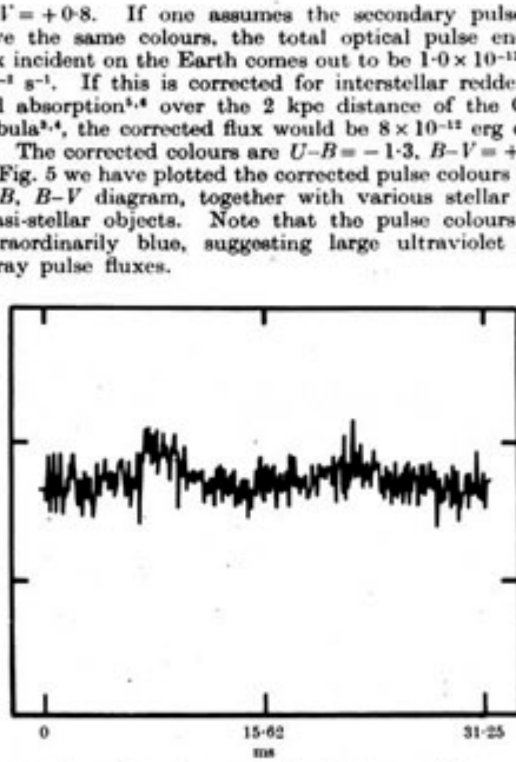

Fig. 4. Strong interpulse recorded through 22 arc s diaphragm on January 17, 1969, 05h 25m UT, summing 3,000 periods.

Fig. 6 gives a plot of the corrected pulse spectral energy flux density with respect to frequency. Note that the density rises sharply into the ultraviolet. The area contained in the dashed quadrilateral represents the total pulse energy flux for the optical band.

The spectral index from U to B wavelengths is $+1.7$, and from B to V it is $+0.3$, whereas a mean spectral index obtained by interpolating from the radio data to the visual is -0.66.

The total average pulse flux in the radio band can also be computed. A rough figure can be obtained using data given by Comella, Craft, Lovelace, Sutton and Tyler[7], from which we get 6×10^{-14} erg cm^{-2} s^{-1}. We see that the corrected optical flux from the pulsar is more than two orders of magnitude greater than the radio flux. It is

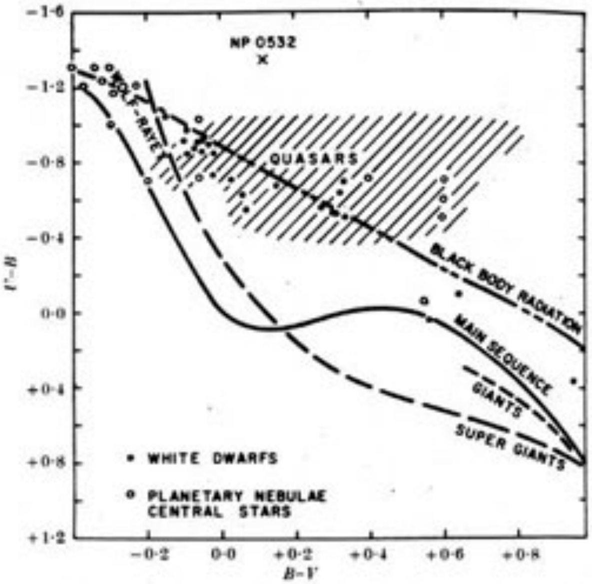

Fig. 5. The unreddened position, ×, of the NP 0532 optical pulses in the ($U-B$) versus ($B-V$) diagram with intrinsically blue objects for comparison.

difficult to estimate the total optical luminosity of the pulses, but if we assume that the Crab Nebula is located at a distance[4] of 2 kpc, and that the pulse radiation is isotropic, the optical pulse luminosity is then 3×10^{33} erg s^{-1}.

The total X-ray flux[8] from the Crab Nebula is roughly 10^{-7} erg cm^{-2} s^{-1} at the Earth. It would be interesting, but certainly extremely difficult, to determine how much of this flux comes from the pulsating source. The position of the X-ray source (Taurus XR-1)[9] is given roughly as somewhere inside the dashed arcs in Fig. 1. Fig. 1 also shows the probable position[10] of the anomalous low-frequency radio source, which contributes substantially to the general radio signal from the Crab below 100 MHz. From interplanetary scintillation studies[11] it has been determined to have an angular diameter less than 1 arc s. The coincidence between the probable positions of the X-ray source, the anomalous radio source and the pulsar is quite suggestive.

We have measured only the magnitudes of the pulses themselves, but we can say that if the south preceding star is indeed the source of the pulses, then the ratio of

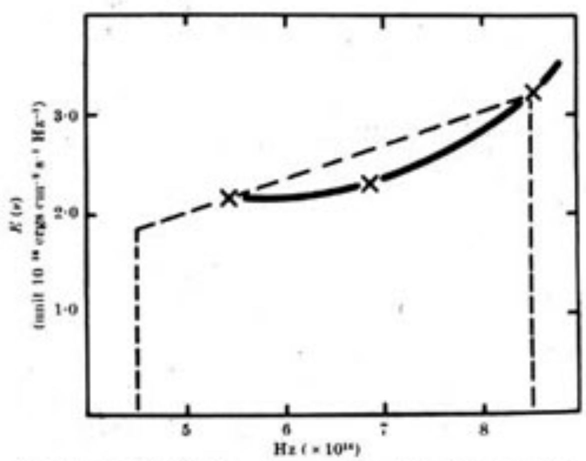

Fig. 6. Spectral distribution of energy arriving at the Earth, corrected for interstellar absorption. The area inside the trapezoid has been used to calculate the total optical flux.

pulse luminosity to total star luminosity is about 10 per cent, because the apparent visual magnitude of the star as a whole[3] is 15·4. According to current neutron star models[13,14], this is an exceedingly high luminosity, for theoretical burning and cooling times for neutron star atmospheres are much shorter than the known lifetime of the Crab Nebula.

The short rise and fall times of the main pulse observed by us ($\approx$ 1·5 ms) imply stringent conditions for any beaming mechanism that might be invoked to explain the pulses. The fact that most of the observed pulse emission is in the optical band seems to indicate that coherent plasma oscillations, as commonly understood, are not the source of the pulse radiation.

We thank R. A. McCallister for aid at the telescope, and W. G. Tifft, R. E. White, W. S. Fitch, R. J. Weymann, G. Muncaster, D. Daer and E. Howell, of Steward Observatory, for help and advice. We also thank R. C. Lynds and S. P. Maran, of Kitt Peak National Observatory, for the loan of equipment, and F. D. Drake for communicating the results of Comella *et al.*[7] before publication.

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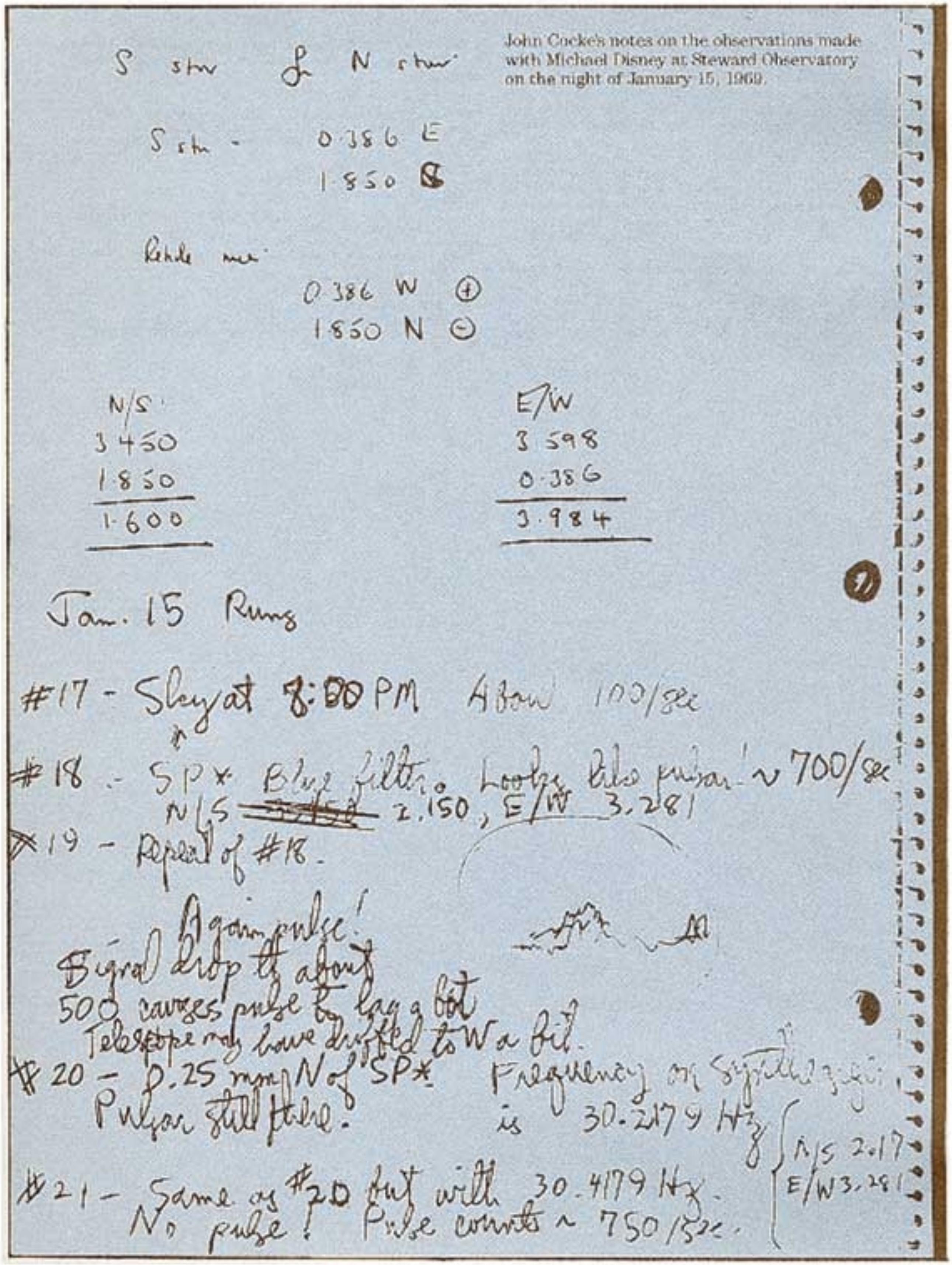
John Cocke's notes on the observations made with Michael Disney at Steward Observatory on the night of January 15, 1969.



John Cocke's notes on the observations made with Michael Disney at Steward Observatory on the night of January 15, 1969.

S star & N star

S star - 0.386 E
1.850 S

Rehde mei:

0.386 W (+)
1850 N (-)

N/S	E/W
3.450	3.598
1.850	0.386
1.600	3.984

Jan. 15 Runs

#17 - Sky at 8:00 PM Above 100/sec

#18 - SP* Blue filter. Looks like pulsar! ~ 700/sec
N/S ~~[illegible]~~ 2.150, E/W 3.281

#19 - Repeat of #18.

Again pulse!
Signal drop to about
500 causes pulse to lag a bit
Telescope may have drifted to W a bit.

#20 - 0.25 mm N of SP* Frequency on synthesizer
Pulsar still there! is 30.2179 Hz

N/S 2.17
E/W 3.281

#21 - Same as #20 but with 30.4179 Hz.
No pulse! Pulse counts ~ 750/sec.

#32. Repeat on SP* Blue filter, Timing Control changed from 10^4 to 7×10^3 ... 11:07 PM. Counts 680/sec. At around 8000 sweeps, the counts dropped to ~150. The pulses are weaker, but there are two close together. Main peak at ch. 350, slightly smaller at ch. 260.

#33. Repeat of #32. Timing control still at 7×10^3 ... 11:19 PM. Counts initially at 740/sec. Main pulse again on channel 0. Minor pulse gone. Decl error about ½ div (upward). Gain at 10^3.

※34. Repeat of 32. 11:29 PM. Pulse good again. Peak at around ch 50. Gain at 10^3 for chart.

#35. SP*. Timing control set back to 10^4. U filter. 11:39 PM. Counts ~ 310. Stopped for guide at 17000 sweeps. Pulse unconvincing. Possibly at ch. 70. Gain on scale below 10^3.

#36. Sky reading. U filter. Counts ~55/sec. 11:49 PM. No pulsar. Gain on test for chart.

#37. Sky on blue filter. 11:57 PM. Counts 100/sec. No pulsar.

Synthesizer [illegible] ... little too fast.

The [illegible] is [illegible] the plotter [illegible] ~ .5 div[illegible]

Then the period error is $\simeq \Delta T/T = \frac{-.5}{400} \times \frac{1}{60} \times .033$

$= \frac{-.5}{2.4} \times 10^{-[illegible]} \times 3.3 [illegible]$

$= -6.9 \times 10^{-6}$

Then $\Delta f = -\frac{1}{T^2} \Delta T = +30 \times 6.9 \times 10^{-6} = +210 \times 10^{-6}$

$= 2.1 \times 10^{-4}$ Hz.

"Pulsars for the Beginner". **Phillip DiLavore and James R. Wayland. The Physics Teacher, May 1971, p. 232.**

Pulsars for the Beginner

Phillip DiLavore and James R. Wayland

I. Introduction

Since the dramatic discovery of pulsars in 1968,[1] some astrophysicists have proposed them to be causative agents of practically every unexplained occurrence in astrophysics. In attempting to understand the mechanisms of pulsar radiation, practically every area of physics has been exploited, and a completely satisfactory theory has yet to be proposed.

However, even the present incomplete models of pulsar behavior offer the possibility of many stimulating examples which could be used to enliven physics courses at several different levels. In this paper we shall discuss illustrations which can be used in an introductory physics course. First, we shall summarize briefly the developments of pulsar investigations and then outline a few illustrative problems from some branches of physics.

II. History

Scientific serendipity, combined with the alertness and receptiveness of trained minds, often has been responsible for discoveries that have initiated investigations in previously neglected directions and that have proved fruitful in fundamental ways. Famous examples are the discovery of the cause and cure of puerperal fever by Semmelweiss, the discovery of x rays by Roentgen, and the discovery of penicillin by Fleming. So too was the discovery of pulsars largely an accident, and it may well lead to a more fundamental understanding of the universe.

In 1967 and 1968, Hewish and his co-workers were routinely mapping intensity distributions of some celestial radio sources, using exquisitely high-resolution methods they had developed. While observing the constellation Vulpecula, they were plagued by periodic "noise" which interfered with the desired observations. After minutely searching for possible sources of electronic and other noise, and eliminating each in turn, they finally decided that the effect was real and that there were indeed periodic radio pulses coming from extraterrestrial sources. Fourier analysis of these pulses showed them to be so precisely periodic that it was seriously suggested that other intelligent beings (Little Green Men) were sending us signals.*

Continued observation and analysis showed that this source was emitting radiation with a period of precisely 1.337301109 sec and was located in the constellation Vulpecula. It eventually was given the name "pulsar" and the designation CP1919, which stands for Cambridge Pulsar at the position in Right Ascension 19^h19^m. (We expect that the television industry will, in the near future, make "pulsar" a household word, eclipsing, so to speak, the "quasar" sets.)

The Cambridge results subsequently were verified by observations made by groups at the University of Manchester[2,3] and at the California Institute of Technology[4]; these results prompted groups at the Arecibo Ionospheric Observatory[5,6] and at the Commonwealth Scientific and Industrial Research Organization[7] to search for and soon observe new pulsars. They shortly were joined by many groups reporting new pulsars at a furious rate.†

III. Observations

Pulsar radiation consists of precisely periodic electromagnetic pulses. These pulses may vary greatly in amplitude and even sometimes disappear. They usually are observed in the radio frequency portion of the spectrum but a few pulsars emit optical and x-ray pulses as well. The radio signals have half-widths ranging from about 1 to 100 msec, and there generally appears "fine structure" which is reproduced from pulse to pulse and which has linewidths on the order of 100 μsec (Fig. 1.).

* In fact, it is rumored that there actually was a search for signals with a period of 1/137 seconds. If observed, such a signal would of course have established the existence of Little Green Physicists out there.

† For comprehensive reviews of the field, see the articles by Maran and Cameron.[8,9] These articles contain detailed references to work in the field, and we shall therefore not cite them here.

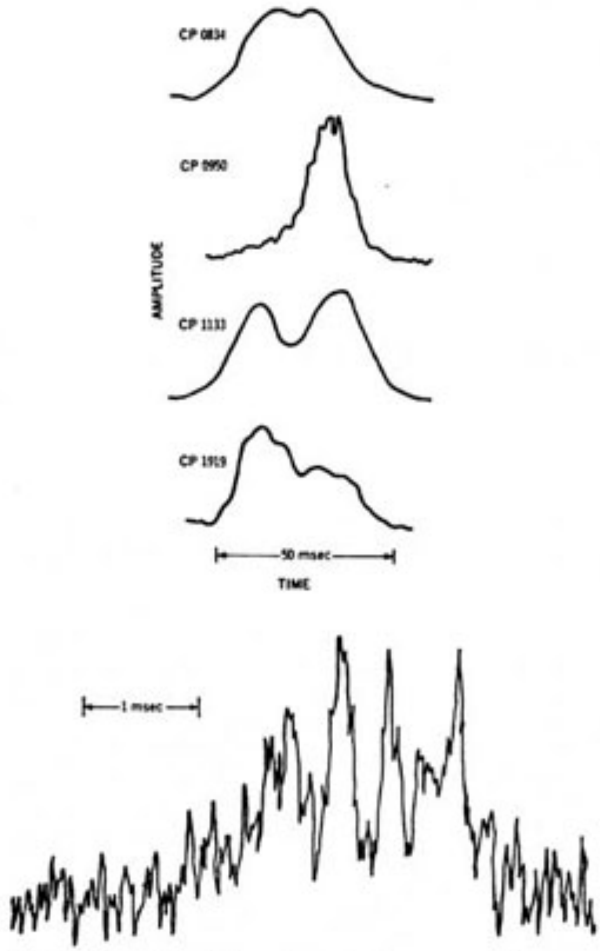


Fig. 1(a). Pulse profiles of four pulsars, showing mean profiles averaged over 8 min at 408 MHz. (Observed at Manchester by Lyne and Rickett; courtesy A. G. Lyne.) (b). A portion of a pulse from CP 1133, showing fine structure. (Moffet and Ekers; courtesy S. Maran.)

This gives us a handle on the approximate size of the emitting region. That is, the fact that the "fine structure" is reproduced in successive pulses indicates that the radiation comes from a single source. This implies that if the source is an extended one, information from any of its regions can reach any other during the time of the pulse. Assuming the maximum possible velocity of information transfer (guess what?) the upper limit of the diameter of the emitting region is about 30 km.

The Crab Nebula, which is the remains of the 1054 A.D. supernova, contains a pulsar that emits pulses of visible light. Considering the standard technique of observing stars—that is, the integration of light over relatively long time periods on a photographic emulsion—it is not surprising that this optical pulsar went undetected through many years of close observation of the Crab. Rather, it was finally detected as a result of a careful search in the region of and in synchronization with the radio frequency pulsar (NP0532). The close synchronization (within 1 msec to present accuracy) of arrival times of radio frequency, optical, and also x-ray pulses from the same small region of space strongly indicates that they originate from a common source.

The interesting implication of this broad spectrum of electromagnetic radiation coming from the Crab pulsar is that it may be related to its short period. Of the many attempts to explain the origin of the pulses, the model which presently has the greatest support from astrophysicists is that of a rotating, magnetic neutron star, as was first suggested by T. Gold.[10] Since some of the pulsars seem to be slowing down, the current model is that of a neutron star whose rate of rotation is decreasing. This slowdown is probably due to loss of rotational kinetic energy in the form of departing electromagnetic radiation.

In the rotating neutron star model, the pulse rate is equal to the rate of rotation of the star. (This mplies, of course, the stupendous rotation rate of up to 60 revolutions/sec for bodies roughly as massive as our sun!) This coupling of the rotational rate and the pulse rate is presumed to be due to the radiation of local concentrations of ions above the surface of the star. These concentrations are thought to arise from the localized trapping of ions in the extremely strong magnetic field of the star following an eruption of material from the surface. The radiation emitted by these ion concentrations is primarily synchrotron radiation, and is strongly directional. Thus, from our vantage point on Earth, the beam sweeps past us much like a search-light beam and results in our observing pulses of radiation.

At least one observed phenomenon is difficult to explain by means of the neutron star model and is not yet understood. That is, for pulsars which emit a main pulse and a smaller subpulse, the subpulse sometimes changes position relative to the main pulse and in effect, sweeps through it as a function of time (see Fig. 2.). This is sometimes accompanied by the mysterious random disappearance and reappearance of the subpulse and/or the main pulse. Another unexplained observation is that the polarization angle of the incoming radiation sweeps through the same change during each pulse from a particular pulsar.

The pulsars observed to date lie predominantly in the galactic plane. This may merely be due to the fact that most of the careful observations have been in that direction. Conclusive evidence awaits the results of current observations throughout the entire sky.

IV. Speculations

When pulsars were first observed in 1968, astrophysicists frantically tried to come up with a physically tenable model to explain their origins. Because of difficulties in matching up the results of any reasonable assumptions with the observed periods, several models were very soon discarded. These included vibrating stars and star systems, extraterrestrial intelligence, and some even farther out

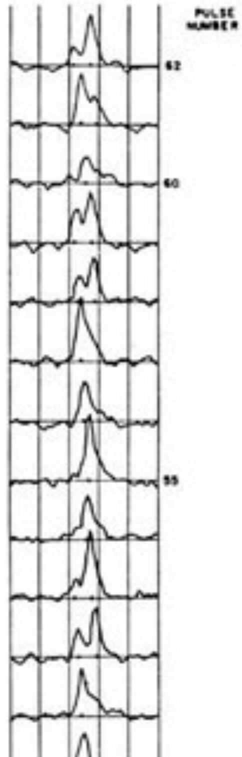


Fig. 2. Fifteen consecutive pulses from AP 2015 + 28, showing the motion of a subpulse through the main pulse from the trailing edge backwards to the leading edge. When the first subpulse approaches the leading edge of the main pulse, a second appears at the trailing edge. (Drake and Croft; courtesy F. D. Drake.)

speculations. But the only model which withstood close examination as being able to produce such precisely periodic pulses was that of a rotating body. Because of the absence of visible light from the pulsars observed to that time, ordinary stars were ruled out. However, astrophysicists have for many years speculated about the possible existence of neutron stars, and when such a model was postulated, the calculations could be made to agree with the observations. In this context, the observation of pulsars is the first, albeit nebulous, experimental evidence that neutron stars may indeed exist.

It is believed that a neutron star is a possible end product of a supernova explosion. In the evolution of a star, there are stages of "burning" of hydrogen, helium, and heavier elements. At each stage of burning—for example during the burning of hydrogen—a temporary equilibrium condition is achieved wherein the gravitational attraction is balanced by outward hydrostatic forces which are produced by the burning. When the element being burned has been consumed, equilibrium no longer exists and gravitational collapse occurs. This raises the temperature of the center of the star to the point that the next heavier element in the burning chain begins to burn and another pause in the gravitational collapse occurs. When the burning reaches a certain critical state (probably after the burning of ^{28}Si) the hydrostatic forces can no longer compete with the gravitational forces and extremely rapid collapse occurs.

In this final process, in the span of a few seconds nuclei become dissociated, protons emit positrons and neutrinos, and the core material becomes primarily neutrons, forming a neutron star. In the process, because of the production of energetic particles and radiation, forces are built up which produce a shock wave which, in turn, forcibly disperses the material which remains outside the neutron star because it has not had sufficient time to be pulled in. It is this scattered material which forms the nebula which produces visible light after a supernova explosion.

When the neutron star is formed, its final radius is about 10^{-5} of the radius of the star which produced it.

V. Illustrative Problems

Although current pulsar models provide illustrations at all levels of analytical sophistication, we shall in this paper give only a few examples which are appropriate to introductory courses. We shall show how one can make simple models which may accurately represent pulsar behavior, and which can be used to get good order-of-magnitude estimates of the measurable quantities involved.

A. Mechanics

The application of basic concepts of mechanics to pulsar models can often give one considerable insight into the mechanisms involved. For example, using the principle of conservation of angular momentum in a straightforward way can tell us a great deal about the final rotational state of a pulsar.

Assuming a homogeneous, spherical mass rotating with angular velocity ω, the angular momentum is

$$L = I\omega = \tfrac{2}{5} MR^2 \omega = \tfrac{2}{5} MR_0^2 \omega_0, \tag{1}$$

where R_0, ω_0 are initial values, and R, ω are values after collapse. (Note the simple assumption of constant mass!) Then the angular velocity after collapse is

$$\omega = \omega_0 (R_0/R)^2, \tag{2}$$

or the period is

$$\tau = \tau_0 (R/R_0)^2.$$

Then, since $R_0/R \simeq 10^5$ and a reasonable period before collapse is $\simeq 2 \times 10^6$ sec (that of our own sun—and we sincerely hope that we will not soon get firsthand experimental evidence of stellar collapse), the new period might be a fantastic 0.2 msec. The Crab pulsar has a period of 33 msec, which is the shortest yet observed. (Even this strikes us as being fantastic!)

In the vernacular, "This baby is really movin'!" The question is, even with enormous gravitational forces present, will it remain whole or will the stupendous rate of rotation cause surface material to be slung off until an equilibrium condition is attained?

Examining a mass element Δm on the surface at the equator, the centripetal force required to keep it there is

$$F_c = \Delta m\, \omega^2 R = \Delta m\, 4\pi^2 R/\tau^2. \tag{4}$$

Using $R_0 \simeq 10^{11}$ cm, which is the radius of our sun, $R \simeq 10^6$ cm, and

$$F_c \simeq \Delta m\, (4\pi^2/4 \times 10^{-8}\ \mathrm{sec}^2) \times 10^6\ \mathrm{cm}.$$

For convenience, use $\Delta m = 1$ g and the result is

$$F_c \simeq 10^{15}\ \mathrm{dyn}.$$

The gravitational force acting upon this same mass element will be

$$F_G = GM\Delta m/R^2. \tag{5}$$

And assuming $M \simeq 2 \times 10^{33}$ g, which is one solar mass,

$$F_G \simeq 10^{14}\ \mathrm{dyn}.$$

Thus, the gravitational force alone is not sufficient to keep the new-born neutron star intact, and surface material would be thrown off until an equilibrium condition is attained. We should note, however, that when neutrons (and some protons) are so densely packed, nuclear forces also will be present and will most likely more than make up the difference required.

At this point, we will proceed to a problem which requires the use of basic calculus. We should like to examine the slowing down of our model pulsar to see if the initial conditions which we just deduced are compatible with observed periods. The easiest way to account for slowing of the pulsar is to assume loss of rotational kinetic energy by a radiation mechanism. The simplest model is that of a magnetic dipole which emits electromagnetic radiation. This radiation, although it might be the principal energy-loss mechanism, should not be confused with the pulsar radiation, which arises from charged particles trapped in the strong magnetic field above the surface. From classical electromagnetic theory, the rate of energy loss is

$$dE/dt = -\alpha\omega^4, \tag{6}$$

where α is a constant depending upon the parameters of the dipole.

Since the kinetic energy is $E = \frac{1}{2} I\omega^2$, $dE/dt = I\omega\, d\omega/dt$, and using Eq. (6),

$$d\omega/\omega^2 = -(\alpha/I)\, dt. \tag{7}$$

Integrating from ω_i, the initial angular velocity at $t = 0$ immediately following stellar collapse, to ω at time t, the result is

$$\frac{1}{\omega^2} = \frac{1}{\omega_i^2} + \frac{2\alpha}{I}\, t. \tag{8}$$

For convenience, let us rewrite in terms of the period, $\tau = 2\pi/\omega$,

$$\tau^2 = \tau_i^2\,[1 + (8\pi^2\alpha/I\tau_i^2)\, t].$$

The quantity $I\tau_i^2/8\pi^2\alpha$ is a characteristic time, which we shall call t_c. Then

$$\tau = \tau_i\,[1 + t/t_c]^{1/2}. \tag{9}$$

We should now like to find a value of t_c for the Crab pulsar. Since we do not know τ_i but can measure both $d\tau/dt$, the rate of slowing, and τ, the present period, let us differentiate Eq. (9):

$$\frac{d\tau}{dt} = \frac{\tau_i}{2t_c}\left(1 + \frac{t}{t_c}\right)^{-1/2}.$$

Eliminating τ_i between the last two equations gives the result:

$$t_c = \frac{\tau}{2\,(d\tau/dt)} - t. \tag{10}$$

The current values for the Crab pulsar are $\tau = 33$ msec and $d\tau/dt \simeq 4.2 \times 10^{-13}$. Since the Chinese observed the Crab supernova in 1054, $t = 916$ yr $\simeq 3.0 \times 10^{10}$ sec.
Then

$$t_c \simeq 9 \times 10^9\ \mathrm{sec} \simeq 300\ \mathrm{yr}.$$

Just what is the physical significance of t_c? To find out, let us get an expression for the kinetic energy of rotation as a function of time and the initial kinetic energy, E_i. We can easily do this by rearranging Eq. (8) and using $t_c = I/2\,\alpha\,\omega_i^2$:

$$\tfrac{1}{2} I\omega^2 = \tfrac{1}{2} I\omega_i^2\,(1 + t/t_c)^{-1},$$

or

$$E = \frac{E_i}{(1 + t/t_c)}.$$

Then t_c is the half-life for the rotational kinetic energy. So the Crab pulsar now has roughly one-fourth of its original kinetic energy.

B. Electromagnetic Phenomena

When considering the magnetic fields which are possibly associated with pulsars, we are again in the realm of speculation. Because of the unimaginable enormity of energetic disruptions during stellar collapse, the processes governing any magnetic fields which might be present are completely unknown. In such a deplorable situation, the poor, struggling theoretical astrophysicist (who must also feed his poor, starving issue like anyone else) can only make plausible guesses as to the mechanisms involved.

One plausible, if somewhat naive, guess is that during the collapse total magnetic flux is conserved.

This approach, which is currently useful, yields the following analysis. If we again assume a star which originally is like Sol, $R_0/R \simeq 10^5$, and the initial magnetic field is typically about 1 G at the surface. Since the flux is magnetic field times area, the scaling law goes like:

$$B = B_0 (R_0/R)^2.$$

So the final magnetic field would be about 10^{10} G.

We should note here that, by measuring the Zeeman splitting of the spectra of atoms at the surfaces of stars, magnetic fields of up to 34, 000 G have been estimated for some stars. So, if we should take a fairly conservative average in the ballpark of 1000 G, the final magnetic field of a pulsar might be about 10^{12} G.

Another interesting thing we can do is to examine the motion of a charged particle in this huge field. Assume an electron moving with the "reasonable" velocity of 2×10^8 m/sec perpendicular to the magnetic field. In mks units, the radius of the circular path resulting is

$$r = mv/qB,$$

where

$$q = 1.6 \times 10^{-19}\ \text{C},$$
$$B \simeq 10^{12}\ \text{G} \simeq 10^8\ \text{Wb/m}^2,$$
$$v \simeq 2 \times 10^8\ \text{m/sec},$$
$$m \simeq 1.2 \times 10^{-30}\ \text{kg}.$$

$$\left[\text{Where this is a relativistic mass, } m = \frac{m_0}{(1 - v^2/c^2)^{1/2}}.\right]$$

Using these numbers, $r \simeq 1.5 \times 10^{-12}$m $\simeq 1.5 \times 10^{-2}$ Å. Since this radius is of subatomic dimensions, it is obvious that classical electromagnetic theory is invalid, and that quantum mechanics must be used in this problem.[11]

C. Thermodynamics

In the area of thermodynamics, we are again speculating. One interesting possibility we might investigate is that pulsars could be blackbody radiators. Using the Planck formula for a blackbody, the intensity (called the "brightness" of stellar sources) is

$$I_f = (2\pi h f^3/c^2)\,[\exp(hf/kT) - 1]^{-1},$$

where

$$h = 6.63 \times 10^{-34}\ \text{J}\cdot\text{sec} = \text{the Planck constant}$$
$$k = 1.38 \times 10^{-23}\ \text{J/°K} = \text{the Boltzmann constant.}$$

(I_f is the energy radiated by a blackbody, which is at a temperature T, per unit area, per second, and per frequency interval df. Its dimensions will be joule/m^2·sec·Hz or, since 1 Hz = 1 sec^{-1}, simply joule/m^2.)

Since the predominant pulsar frequencies are at a few hundred megahertz, any temperature above 1° K makes $hf/kT << 1$, any the exponential can be expanded to $\simeq 1 + hf/kT$, so that the Planck function becomes (the Rayleigh–Jeans case)

$$I_f \simeq 2\pi kT f^2/c^2,$$

or, we now have a brightness temperature defined in terms of measurable quantities and known

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constants:

$$T \simeq I_f c^2 / 2\pi k f^2. \qquad (11)$$

It is now easy to do a rough, order-of-magnitude calculation using figures for a "typical" strong pulsar. The observed flux at the earth may average about 10^{-26} J/m^2·sec·Hz at 500 MHz. Assuming a distance from the pulsar to the earth of 1 parsec ($\simeq 3 \times 10^{13}$ km) and a pulsar diameter of 10 km, and also assuming that equal amounts of radiation pass through the two spheres of these respective radii, the average flux at the pulsar is the ratio of the areas of the two spheres times the flux at the earth, or about 0.1 J/m^2. (Yes, Virginia, we know that the radiation is not isotropic, but this is a *rough* calculation.) Using these numbers, the brightness temperature arrived at is an incredible 4×10^{20} °K! Thus it is reasonable to assume that the model of a blackbody radiator for a pulsar is not a reasonable assumption. (The temperature of the interior of the sun, for example, is about 2×10^{7} °K.)

VI. Further Thoughts

Our first impulse was to write a conclusion to this brief paper. But some slight reflection convinced us that here, as in *2001*, we have come to the beginning. We hope that this effort has the effect of enlivening physics courses to a slight degree. But further, we hope that others will think highly enough of the idea to try to develop some problems in other current topics which can be tackled by students in introductory courses.

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"A Pulsar Detected Optically" **Sky and Telescope, p. 135 (March 1969).**

A Pulsar Detected Optically

AMONG the rapidly pulsating radio sources, NP 0532 has held a special importance ever since its discovery last October at the National Radio Astronomy Observatory. Its position coincided with the Crab nebula, expanding remnant of the supernova explosion of A.D. 1054. Its period of 33 milliseconds (0.033 second) was the shortest yet found, and moreover was lengthening perceptibly from week to week (see SKY AND TELESCOPE for January, pages 3 and 24).

More recently, NP 0532 has become the first pulsar whose light variations have been unmistakably observed. (The attempts last year at optical detection of CP 1919, described in the July, 1968, issue, page 6, were never confirmed.) At least four teams of investigators have detected the flickering of NP 0532. It has been monitored photoelectrically, photographed, and even seen through observatory telescopes.

The first detection was by W. J. Cocke, M. J. Disney, and D. J. Taylor, with the 36-inch reflector of Steward Observatory, University of Arizona. On January 15th and 16th, their photoelectric search of the central part of the Crab nebula revealed flashes that came every 33.095 milliseconds and were of four-millisecond duration. Occasionally, a secondary pulse appeared midway between two primary pulses. The peaks of the flashes were about magnitude 15, while the time average over a cycle was magnitude 18.

The Steward observers place this optical source about six seconds of arc from the southwestern star of the faint pair at the Crab nebula's center. This may be called Baade's star, because Walter Baade suggested in 1942 that it was possibly the object that excites the Crab to shine. According to him, this star is of magnitude 15.90 photographically and 15.45 photovisually.

A detailed confirmation was obtained on January 19th and 20th at McDonald Observatory in Texas, by R. E. Nather, B. Warner, and M. MacFarlane, using the 82-inch reflector. Mr. Nather, chief electronics engineer at the observatory, designed and built the special equipment for this difficult task. Because only a few photons are received during any one cycle, signal averaging techniques of great precision are needed.

Pulse signals from the photoelectric photometer were amplified and counted on a 400-channel multiscaler, whose accumulation cycle was synchronized with the pulsar period. Fortunately, sky conditions were excellent on the 19th, and with the instrumental period set at 33.095 milliseconds the flashing was quickly located.

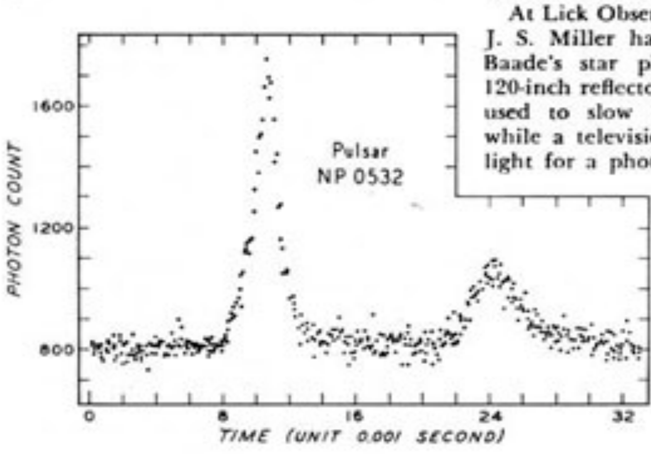
The McDonald team found, by observing with a photometer diaphragm 3.6 seconds of arc across, that the object is essentially a point source. Visual inspection through a larger diaphragm showed the pulsar itself, marginally visible against the bright nebular background.

On the 19th, the heliocentric period was determined as 33.093464 milliseconds, on the next night as 33.093487. To obtain these figures, the apparent periods had to be corrected for the earth's orbital and rotational velocities. As the mean light curve by the Texas astronomers shows, the main pulse is followed at 13.6 milliseconds by a lower secondary pulse.

At Kitt Peak National Observatory in Arizona, the optical pulsations of NP 0532 were observed photoelectrically on January 20th with the 84-inch reflector by R. Lynds, S. P. Maran, D. Trumbo, G. Grueff, and J. De Veny. Using a photometer diaphragm as small as two seconds of arc, they established that the light pulses were coming from the position of Baade's star.

They synchronized the memory unit of their photometer to twice the apparent period of 33.0955 milliseconds, and thus were able to compare alternate primary pulses. No systematic difference was found between odd and even pulses.

At Lick Observatory E. J. Wampler and J. S. Miller have verified the flicker of Baade's star photographically with the 120-inch reflector. A spinning shutter was used to slow the rate stroboscopically, while a television scanner stored enough light for a photographic image.



A mean light curve of the pulsar NP 0532 from photon counts for 380 seconds. The peak corresponds to apparent magnitude $V = 14.4$. McDonald Observatory diagram for *Nature*, courtesy Harlan J. Smith.

Table of contents from David and Smith, ed., *The Crab Nebula*,
Inernational Astronomical Union Symposium no. 46, Aug. 5-7, 1970.

Table of contents from Davies and Smith, ed., *The Crab Nebula*,
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Please Type

Principal Investigator ______________________________

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(Please ensure that the names in this section are identical to those on page 6)

Program ______________________________

____

1) Summarize in two or three sentences the aim of the program.

2) Observing runs requested this semester for this project:

Run	Telescope	Instrument(s)	Nights	Days
1				
2				
3				
4				

Run	Lunar Phase Required*	Range of Optimum Dates	Range of Acceptable Dates**
1			
2			
3			
4			

* Maximum days from new moon for full night operation.
** Extreme limits of the range of dates that could reasonably be assigned to this project. Please be realistic. A range of less than three months should be explicitly justified.

3) Dates you cannot use for non-astronomical reasons ______________________________

____

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4) Scientific justification, Part I: Discuss the specific objectives of your observing program and the significance of the program to astronomy. Please confine your response to this page. (Do not cite material from earlier observing requests since that previous material is not available to the TAC.) DO NOT inlcude preprints or other attachments (except for visitor equipment needs) since they cannot be distributed to Committee members.

5) Scientific Justification, Part II: Detail your plans for obtaining, reducing and analyzing the data. You should try to sketch a plausible path from the telescope to the goals outlined on the previous page. If the program is a continuation of one previously approved, begin with a progress report.

6) Justify the AMOUNT of observing time requested (e.g., number of objects and the exposure time per object). List the objects, positions, magnitudes and other properties defining the observational program.

7) Allocations of all telescope time (at KPNO and elswhere) during the past two years. Indicate current disposition of data, publications comopleted (give references) or in preparation, or any additional information you consider relevant. The TAC is interested in both experience and the effectiveness with which previous time has been used.

8) If the requested time is allocated and the observations successfully obtained, how many additional clear nights or days at KPNO will be required to complete this project? ________

9) If the facilities of other observatories are being used in this and other projects, give details.

10) In some cases applicants have access to observing facilities through their home institutions. If this is the case, please explain the need for KPNO facilities.

11) Telescopes, auxiliary equipment, and special software requirements. Detail the instrument required for each type of observation, other auxiliary instruments required, and expendable supplies, such as photographic plates, chemicals, bottled gases, and cryogenics.

* If you plan to do photometry, specify type of data acquisition, filters, coldbox, and photomultiplier required.
* If you may require any special instrumental or software support, no matter how trivial, provide the complete details.

12) Visitor Equipment. If you plan to bring your own equipment, you must attach to the Observing Time Request form an additional page giving the following information: a detailed description of the equipment you would like to bring and how you plan to use it in connection with our telescopes. It is essential that the technical staff understand your requirements. We cannot do a proper review unless you provide sufficient information.

13) Travel Support. Travel support is generally limited to one visitor user per observing session except in the case of a graduate student doing thesis work. In such cases, KPNO will pay full travel for the student plus the deductible for another observer.

A. Name of Investigator who will claim deductible: ________________________________

B. Name of graduate thesis student who will claim support: ________________________

C. The responsible faculty astronomer must indicate in a letter accompanying <u>each</u> proposal whether or not the student is planning to do the work of his/her dissertation, and also certify that the student is in good academic standing and is capable of carrying out the program.

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This exhibit is based on the educational package, *Moments of Discovery, Unit 2: A Pulsar Discovery*, by Arthur Eisenkraft with Lilllian Hoddeson, Joan N. Warnow, Spencer Weart, and Charles Weiner, published by the American Institute of Physics in 1984.

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