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This Week's Citation Classic®

Gold T. Rotating neutron stars as the origin of the pulsating radio sources. *Nature* **218**:731-2, 1968; and **Gold T.** Rotating neutron stars and the nature of pulsars. *Nature* **221**:25-7, 1969.
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Enigmatic, rapidly pulsating radio sources were interpreted as rotating beacons sweeping over the Earth, radiating out from rapidly rotating, extremely collapsed stars ("neutron stars"). Numerous detailed predictions followed from this model, and all were soon verified. The model also accounted closely for the previously unexplained luminosity of the Crab Nebula. [The *SCI*® indicates that these papers have been cited in more than 240 and 150 publications, respectively.]

The Nature of Pulsars

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The Cambridge radio astronomy group announced, in two papers in February and April 1968, the startling observations of rapidly recurring short radio pulses from four sources in the sky; each had a constant pulse repetition frequency ranging from 1/4 second for the fastest to 1.33 seconds for the slowest.[1,2]

How could any object at astronomical distances transmit sufficient energy in brief pulses, so as to be observable here? The source had to be small, so that the light time across it would not lengthen the pulses beyond the few milliseconds observed. A calculation gave almost unbelievably high values of the required intensity at the source.

At a conference in London in 1951[3] I had argued that dense, collapsed stars would be ideally suited to emit strong radio signals, since their magnetic fields may be enormously strengthened by the collapse and extend out into low density space. But such objects would be expected to show rapid time variations, not present for the radio sources then known. I therefore preferred to attribute these sources to distant galaxies, not to stellar objects.

The pulsars now seemed to represent just the stellar objects I had discussed then. Calculations existed for the collapsed "neutron stars" that indicated approximately their size, as small as a few kilometers, and their mass, on the order of a solar mass.[4] Astronomers generally thought that even if they existed, they could never be discovered. However hot, a star so small could not be seen at astronomical distances. But they had not considered the energy concentration resulting from the collapse: enormous magnetic field strengths and a spin energy quite comparable with the entire content of nuclear energy of the star before its collapse. With these considerations it was not unreasonable to expect them to be observable.

I had another clue to the nature of the new objects: While there was some irregularity in the pulse-to-pulse timing, the long-term accuracy of these "clocks" was enormously better than a statistical addition of the pulse irregularities would have allowed.

I proposed the model of a rapidly spinning neutron star, which, as a result of some asymmetries, sent out a strong beam of radiation from one region of longitude. This beam would sweep over the Earth once in each rotation period and would be seen as a short pulse. The underlying long-term accuracy would then be produced by the spin of the object, while short-term timing fluctuations would just reflect details of the emitting mechanism. I compared it to the rotating beacon of a lighthouse, whose lamp, hanging from the rotating shaft, could wobble a little; the long-term accuracy would still be that of the rotation of the shaft.

My submission to *Nature* explained these points and predicted that pulsars might be found in the location of

supernova explosions, since neutron stars may be products of that process; I also noted that fresh neutron stars could be expected to rotate considerably faster than the pulsars so far discovered, and one should therefore search for shorter periods. Moreover, if rotation was the energy source, one should be able to observe a slight slowdown in this long-term clock.

A conference on pulsars was organized in New York for May 20 and 21. Many speakers and some of the original discovery group were invited. I had sent my paper to the organizers with the request for a five minute slot, but this was turned down: "The suggestion was so outlandish that if this was admitted there would be no end to the number of other suggestions that would equally have to be allowed."[5]

Meanwhile, the editor of *Nature* obviously thought otherwise. The paper, received on May 20, appeared on May 25, probably a record in publication speed for the journal.

The New York conference was a fiasco, dominated by a report of startling new observations that turned out to be entirely false and by theoretical models of radially pulsating white dwarf stars.

But I did not have to wait long for the confirmations of my theory. By October of that year, the Australians reported the detection of a pulsar with an 89 millisecond period, the shortest then known, and that in a location of a rather recent (20,000 year old) supernova explosion.[6] In November the Arecibo Observatory in Puerto Rico, a facility under my direction, made the clinching discovery: the fastest pulsar to date, a 33 millisecond repetition frequency, was found in the Crab Nebula, the site of the most recent supernova known (914 years old).[7] Within a day the expected slowdown was also observed.

The Crab Nebula luminosity of about 100,000 times that of the sun now had an explanation. The observed value of the slowdown and the moment of inertia of a neutron star implied an energy loss that closely matched the observed luminosity of the nebula. Evidently, energetic particles, fed by the rotational energy, were responsible. Atthis stage there were no doubts left about the explanation, and I submitted this result in the second paper to *Nature,* received there on December 10.

A great new era in astronomy had begun. A world of very high density, very high energy concentration had opened up. Here relativity theory was supreme, not a minor correction to Newtonian gravitation. It was a world not only of strong radio pulses, but of X-rays and high energy particles. The knowledge that neutron stars with masses and densities close to the relativistic configuration of a black hole really existed meant that black holes probably also existed. Pulsar observations have given us by far the most accurate confirmations of general relativity, and the first observations of the process of emission of gravitational waves,[3] as well as many other new astronomical data.

In the citation for the award to me, in 1985, of the Gold Medal of the Royal Astronomical Society of Great Britain, my identification of the nature of pulsars was the lead item.

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3. **Gold T.** The origin of cosmic radio noise. (Lang K R & Gingerich O, eds.) *A source book in astronomy and astrophysics. 1900-1975.* Cambridge, MA: Harvard University Press, 1979. p. 782-5.
4. **Oppenheimer J R & Volkoff G M.** On massive neutron cores. *Phys. Rev.* **55**:374-81, 1939. (Cited 310 times since 1945.)
5. Cameron A G W. Personal communication, 1968.
6. **Large M I, Vaughan A E & Mills B Y.** A pulsar supernova association? *Nature* **220**:340-1. 1968.
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8. **Taylor J H & Weisberg J M.** Further experimental tests of relativistic gravity using the binary pulsar PSR 1913+16. *Astrophys. J.* **345**:434-50. 1989.

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