Title
POSSIBLE GRAVITATIONAL COLLAPSE INTO A BLOCK HOLE OF THE PULSAR IN SUPERVOVA 1987A

Author
Glendenning, N. K.

Publication Date
1989-11-01

UC-413

LBL-26978 Rev.
Preprint

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

Possible Gravitational Collapse into a Black Hole of the Pulsar in Supernova 1987A

N.K. Glendenning

November 1989

NUCLEAR SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

DISCLAIMER

Possible Gravitational Collapse into a Black Hole of the Pulsar in Supernova 1987A†

Norman K. Glendenning

Nuclear Science Division

Lawrence Berkeley Laboratory

1 Cyclotron Road

Berkeley, California 94720

May 2, 1989

Revised November 30, 1989

†This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of Nuclear Physics, of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

Possible Gravitational Collapse into a Black Hole of the Pulsar in Supernova 1987A†[0]

Norman K. Glendenning

Nuclear Science Division

Lawrence Berkeley Laboratory

1 Cyclotron Road

Berkeley, California 94720

May 2, 1989

Revised November 30, 1989

Abstract

We discuss how recapture of a object from debris spewed at the early stage of formation by the millisecond pulsar whose signals where observed briefly in the remnant of SN1987A may have caused its subsequent collapse into a black hole, by damping the rapid rotation which is believed to have contributed to its stability. The mass of the object sufficient to bring this about in the two week interval between observation and next search is calculated to be up to 1/20 of a Jupiter mass.

PACS 97.60-s, 95.30.Sf

[0]†This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of Nuclear Physics, of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

Possible Gravitational Collapse into a Black Hole of the Pulsar in Supernova 1987A

Norman K. Glendenning

May 2, 1989
Revised November 30, 1989

Half millisecond pulses from the center of the remnant of SN1987A, modulated by an eight hour period, were discovered on the night of January 18, 1989 UT and have been interpreted as due to the orbital motion of a very fast pulsar with a companion of about a Jupiter mass [1]. About sixty million pulses were recorded on that night, sufficient to provide a measurement of the rate of change of the period, $\dot{T} < 3 \times 10^{-14}$ s/s. The signal, which had this extraordinary stability, was not seen two weeks later when next searched for, nor has it been seen since. We shall explore a scenario in which a rapidly spinning neutron star will subside into a black hole within the two week interval between first sighting and next search, due to the recapture of a small low-mass object ejected at the early stage of formation of the pulsar and the consequent braking of the rotation to a sub-critical value due to the gravitational radiation caused by the aspherical transport of the captured object. The constraints found for the object are that it has a sub-Jupiter mass up to $\frac{1}{20} M_{Jupiter}$. Interestingly, since this suggestion was made [2, 3], the discovery team has found independently, in the improved analysis of their data, evidence for a 2 hour frequency modulation that can be interpreted as a *second* companion on a highly eccentric orbit and of about the mass needed in our scenario [4].

Of course the most plausible reason for a *temporary* disappearance of the pulsar is that it has been obscured by a cloud of debris from the supernova which meanwhile has moved into the line of sight because of its angular velocity. However this account becomes less plausible with time because if nothing else happens to the pulsar itself, then it will reappear as the cloud becomes less opaque due to its expansion or as the cloud is carried away by its angular velocity. Intermittency of the pulsar signal is another possibility, but seems unlikely, again because of the passage of time since the sighting. Yet another (exotic) account of the disappearance is slow precession due to a very small deformation with axis inclined to the rotation axis [5]. In this event the pulsar should reappear cyclically.

The key to the scenario outlined in the first paragraph is the observation that a rapidly spinning compact star can be stabilized at a mass that is greater than the limiting mass of a star with the same baryon number but lower frequency [6]. This is almost certainly the case for this millisecond pulsar as the studies of Friedman, Ipser and Parker [7] and Sato and Suzuki [8] suggest. Assume that, following the main supernova explosion, the collapsing core had angular velocity that exceeded the limit for its mass and that it shed matter in the equatorial plane, of which the observed Jupiter-mass companion is one product. This is plausible since the companion is unlikely to have survived the explosion had it been formed earlier. Because the eight hour frequency modulation of the millisecond signals from the pulsar is rather closely sinusoidal, with only small deviations, the Jupiter-mass companion must form the bulk of material in orbit with the pulsar but it is unlikely that all of the matter expelled was so coherent as to form a single companion because of the turbulent conditions. We suppose that one additional small object, its orbit damped by gravitational radiation and perturbed by the other companion, the pulsar and the dirty environment of the pulsar described below, has fallen back onto the surface of the pulsar near the equatorial plane from which it was first ejected, creating an aspherical transport of matter. Since the star will have cooled substantially in the intervening two years since its birth to ~ 100 KeV temperature the dense matter is highly degenerate and the viscosity is expected to be high. The captured object is expected to remain localized for tens of years from the estimate of the viscous damping time of neutron star matter by Comins [9] as interpreted by Friedman et al. [6]. In this event the pulsar now has a time-varying mass quadrupole moment which will produce gravitational waves and damp the pulsar's rotation. We calculate how massive the recaptured object must have been so that the resulting gravitational radiation will have damped the rotation sufficiently in two weeks to bring it below the critical angular velocity that provides the marginal stability against collapse to a black hole.

For a spherical rotating star of radius R and mass M with a lump of mass m attached at its equator, the angular velocity, ω, is damped by gravity waves according to

$$\dot{\omega} = -16\frac{m^2}{M}R^2\omega^5 \equiv -A\omega^5 \tag{1}$$

From this find the period doubling time,

$$t_{(2)} = \frac{15}{4A}\frac{1}{\omega_0^4} \approx 2.7 \times 10^{10}\frac{M}{M_\odot}\left(\frac{M_\odot}{m}\right)^2\frac{T_s^4}{R_{10}^2} \quad s \tag{2}$$

where T_s is the period of the pulsar in seconds and R_{10} is its radius in units of 10 km. Assuming that the pulsar's observed frequency is near the limit for its mass we estimate from the tables of Friedman, Ipser and Parker [6] that the mass is $\approx 1.66M_\odot$ with a radius of $R \approx 11$ km. We find from Eq. (2) that the mass of the lump must have been $m \approx 4.4 \times 10^{-5}M_\odot \approx \frac{1}{20}M_{Jupiter}$ so as to double the period in two weeks. This appears not to be unreasonably large, its mass being constrained from above qualitatively by the small degree of perturbation of the pulsar's orbit as inferred from its frequency modulation. The effects of period doubling of pulsars near the limiting frequency is drastic as can be inferred from Fig. 1 of Ref. [6] so that the above mass is more than sufficient to destabilize the pulsar in two weeks.

For the proposed scenario to work, the captured object must satisfy the two mass constraints stated above (sufficiently large to destabilize the pulsar within two weeks but sufficiently small compared to the Jupiter-companion as not to appreciably alter the sinusoidal frequency modulation). Also it must not be torn apart by tidal forces and it must be small compared to the pulsar so that its mass is localized after capture. There are no known astrophysical objects of $M \approx \frac{1}{20}M_{Jupiter}$ which are small compared to expected pulsar dimensions ($R \sim 10$ km) excepting for a small black hole, or a conjectured [10] strange quark nugget. Planets and white dwarfs are much larger in size, and in any case would be destroyed by tidal forces and accreted as dust at a rate consistent with the Eddington limit. Elsewhere it has been noted that the new pulsar itself may be a strange quark star [11, 12]. Indeed a rather compelling case has been developed, on several grounds, that it is not a neutron star but rather is a strange star [13, 14, 15]. The main points are: (1) The central density of neutron stars models (we have studied more that 1440 models in a gridded search) that satisfy the double constraint of sufficient mass and fast rotation are so high that it is implausible that such matter can be composed of individual hadrons. (2) The window in mass or baryon number of a neutron star would have to be fine tuned to support fast rotation. (3) Hybrid stars (quark core in equilibrium with neutron star exterior) are also implausible, since to satisfy the double constraint, the equation of state must be stiff at high density, which is incompatible with the notion of asymptotic freedom. Again, such stars would have to be fine tuned in mass to support fast rotation. (4) Strange quark stars, if strange matter is the absolute ground state, can support such fast rotation. Indeed the entire family can do so provided only that strange matter is self-bound at an energy density greater than 5.4 normal nuclear density. According to the discussion of the conversion of a neutron star to a strange star, and their likely mass, density and size relationships [13], the pulsar will have spun up on conversion, by a factor of 3-4, and must have shed mass, possibly $1/2M_{\odot}$ or more to evade becoming a black hole. (The limiting mass of a strange star is likely to be smaller than the limiting mass of the progenitor neutron star, since the equation of state of quark matter is expected, on grounds of asymptotic freedom, to be softer than that of neutron matter.) For these reasons, it seems most likely that the small sub-Jupiter companion is a strange nugget [13, 12]. Its average energy density must exceed 5.4 times normal nuclear density, since this is the lowest density at which strange matter must be self-bound if it is to sustain the rapid rotation of the new pulsar [16]. This result is independent of any particular model of self-binding or confinement. The strange quark nugget can therefore easily withstand the tidal forces of the pulsar and can be expelled without breaking up. The same is true of the Jupiter mass companion if it is strange, but not if it is a planet. Not all of the ejected material is expected to be strange matter however. Some of it will be unconverted neutron star matter, including nuclei from the outer reaches of the precursor neutron star that will have converted from the inside out. Such matter will be ground to dust by the tidal forces.

The dirty environment created by the ejecta, provides an additional rationale for the damping and recapture of the sub-Jupiter companion from its highly elliptical orbit. It also provides a possible reason why the expected gamma ray burst that would accompany the recapture could have been so strongly attenuated as to go unnoticed, although this event has a fifty percent chance of being eclipsed by the pulsar itself. The very high bulk viscosity of quark matter (compared to neutron matter) computed by Sawyer [17] provides additional reason for believing that the recaptured nugget remains localized for the two week interval during which the gravitational spin-down of the pulsar occurs in this scenario.

The scenario proposed above shows that whether or not the newly born pulsar has subsided into a black hole by now, it is in peril of doing so promptly following the aspherical capture of an object having mass of the above order, ie of the order of the mass of the second companion.

While the central idea outlined above is very simple, we have invoked several attendant phenomena. However they seem to flow very naturally from the interpretation of the fast pulsar as being a strange quark star.

Whether "last gasp" signals emitted just prior to disappearance of a compact star into a black hole could be observed depends to a large degree on the brevity of the final collapse, since a concentrated pulse of neutrinos or gravitational radiation is more easily detected than a long one carrying the same energy.

If this scenario does indeed describe the fate of the young pulsar so fleetingly glimpsed in January, then we have witnessed a remarkable sequence of events that is not likely to occur again for many generations, a spectacular supernova display whose equal has not occurred in this part of the universe since the Crab supernova 900 years ago, the birth of a neutron star at its center, followed soon after by its disappearance into a black hole.

Acknowledgements: I appreciate helpful discussions with C. R. Pennypacker,

M. G. Redlich and W. J. Swiatecki . This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of Nuclear Physics, of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

References

[1] J. Kristian, C. R. Pennypacker, J. Middleditch, M. A. Hamuy, J. N. Imamura, W. E. Kunkel, R. Lucinio, D. E. Morris, R. A. Muller, S. Perlmutter, S. J. Rawlings, T. P. Sasseen, I. K. Shelton, T. Y. Steinman-Cameron and I. R. Tuohy, NATURE **385** (1989) 234.

[2] N. K. Glendenning, LBL-26978, March 1989.

[3] N. K. Glendenning, *Neutron Stars, Fast Pulsars, Supernovae and the Equation of State of Dense Matter* in NATO Advanced Study Institute, "The Nuclear Equation of State", ed. by W. Greiner, Peniscola, Spain, May 21-June 3, 1989, To be published by Plenum, London (LBL-27293).

[4] J. Middleditch et. al. *Further Analysis of the PSR1987A Discovery Data*, preprint, Aug, 1989.

[5] N. K. Glendenning, Phys. Rev. Let. **63** (1989) 1443.

[6] J. L. Friedman, J. A. Ipser and L. Parker, Astrophys. J. **304** (1986) 115.

[7] J. L. Friedman, J. A. Ipser and L. Parker, Phys. Rev. Let. **62** (1989) 3015.

[8] K. Sato and H. Suzuki, Prog. Theoret. Phys. (Tokyo) **81** (1989) 997.

[9] N. Comins, Mon. Not. Royal Astron. Soc. **189** (1979) 233.

[10] E. Witten, Phys. Rev. D **30** (1984) 272.

[11] N. K. Glendenning, *Physics of Dense Matter, Neutron Stars and Supernovae* Fifth Workshop on Nuclear Astrophysics, Tergensee, Germany, January 30 - February 4, 1989 (LBL-26895).

[12] J. A. Frieman and A. V. Olinto, Nature **341** (1989) 633.

[13] N. K. Glendenning, J. of Phys. G, **15** (1989) L225.

[14] N. K. Glendenning, *Fast pulsar in SN1987A: Canditate for strange quark matter*, July 7, 1989 (LBL-27446).

[15] N. K. Glendenning, *Supernovae, Compact Stars and Nuclear Physics*, invited paper, Proc. Int. Nucl. Phys. Conf., Sao Paulo, Brasil, August 1989, (to be published by World Scientific Publishing Co) (LBL-27747).

[16] N. K. Glendenning, *Strange-Quark-Matter Stars*, invited paper, Rio de Janiero International Workshop on Relativistic Aspects of Nuclear Physics, August 1989, (to be published by World Scientific Publishing Co).

[17] R. F. Sawyer, *Damping of Vibrations and of the Secular Instability in Quark Stars*, Preprint: UCSBTH-89-33.