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March 1989

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

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March 28, 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.

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Abstract

We discuss how recapture of a lump from debris spewed at the early stage of formation by the millisecond pulsar whose signals were 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 lump sufficient to bring this about in the two week interval between observation and next search is calculated to be about $1/20$ of a Jupiter mass.

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

Norman K. Glendenning

March 28, 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 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 is a black hole of mass up to $\frac{1}{20} M_{Jupiter}$.

The key to this scenario is the observation that a rapidly spinning neutron 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 [2]. Assume that 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 companion is one result. This is plausible since the companion is unlikely to have survived the explosion had it been formed earlier. Having shed substantial matter in the initial turbulent stage of birth suppose that one such small object, its orbit damped by gravitational radiation, has fallen back onto the surface of the neutron star near the equatorial plane from which it was first ejected, creating an aspherical transport of matter in the neutron star. Since the neutron 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 lump will produce a region of higher than average density and is expected to remain localized for tens of years, from the estimate of the viscous damping time of neutron star matter by Comins [3] as interpreted by Friedman et al. [2]. We calculate how massive it must have

been so that the resulting gravitational radiation will have damped the rotation sufficiently in two weeks to bring the star below stability so that it will collapse to a Kerr-Newman 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

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

From this find the period doubling time,

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

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 [2] that the mass is $\approx 1.66 M_\odot$ 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. [2].

Whether "last gasp" signals emitted just prior to disappearance of a neutron 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.

For the proposed scenario to work, the captured lump must not only satisfy the two mass conditions stated above but it must not be torn apart by tidal forces and it must be small compared to the neutron star 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 neutron star dimensions ($R = 10 - 15$ km) excepting for a small black hole. 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. Exotic stars have been conjectured (see refs. [4,5,6] and cited references) that can fall in the desired size and mass range, but they are more likely to have been created in the early universe, if any of them exist, than in the collapse of a star. Black holes accrete background radiation (3°K) or evaporate according to whether their mass is greater or less than $\sim 10^{-7} M_\odot$, so that we have no concern that the conjectured small black hole originating in the turbulence of the supernova will have evaporated in the intervening two years.

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. This conjecture

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. In any case 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 a lump having mass of the above order.

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.

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