LETTERS TO THE EDITOR

ASTROPHYSICS

Possible Magnetospheric Phenomena associated with Neutron Stars

With the discovery of X-ray sources in the sky[1,2], speculation has arisen that they might be associated with neutron or hyperon stars formed during the internal collapse which triggers off supernova explosions (probably of type I). Rates of cooling of neutron star models have been calculated by Morton[3], Chiu and Salpeter[4,5], and Tsuruta[6]. It appears (J. Bahcall, personal communication) that the importance of the early cooling by emission of neutrinos from the 'Urca' process has been underestimated in the foregoing investigations. With rough allowance for this effect, the calculations of Miss Tsuruta indicate that a neutron star will rapidly cool to 3 or 4 $\times 10^6$ °K, but that after 10^5 years its surface temperature will still be about 2×10^6 °K.

During the earlier part of 1964 evidence unfavourable to the neutron star hypothesis for X-ray sources accumulated. Thus Bowyer, Byram, Chubb and Friedman[7] showed from a lunar occultation measurement that the diameter of the X-ray source associated with the Crab Nebula is about one light year, and there appeared to be a deficiency of soft X-rays from it. At the symposium on "Neutron Stars and Celestial X-ray Sources", held at the Goddard Institute for Space Studies during March 1964, Giacconi and Friedman both reported crude spectral estimates which suggested that the strongest X-ray source, in Scorpius, if thermal, would have a temperature of about 1 or 2×10^7 °K—much too hot to be interpreted as a neutron star.

Many more measurements were reported at the second Texas Conference on Relativistic Astrophysics in December 1964. Friedman, for example, reported that the soft X-ray flux from both the Crab Nebula and the Scorpius source has been greatly underestimated; his newer determination of the equivalent thermal temperature of the Scorpius source was 2×10^6 °K. He also reported that ten X-ray sources had now been identified and that these formed a distribution flattened toward the galactic plane. Also at the December 1964 Texas Conference Giacconi reported that the angular diameter of the Scorpius source is less than 8 min of arc. However, Clark, at the same Conference, reported that the Crab Nebula emitted a significant flux of ~ 30 keV X-rays, consistent with the synchrotron emission picture of Woltjer[8]. Fisher, again at the second Texas Conference, reported that the X-ray energy spectrum from the Scorpius source contained too large a flux of higher energy X-rays to be consistent with a pure thermal spectrum of 2×10^6 °K.

It is the purpose of the present communication to suggest that the discrete X-ray sources may be neutron stars with an associated magnetosphere. The X-ray spectrum would thus consist of a thermal component emitted from the photosphere and a non-thermal synchrotron component emitted by trapped electrons accelerated in the magnetosphere.

Magnetic fields are commonly associated with stars. Woltjer[8] has pointed out that neutron stars may contain magnetic fields with strengths up to $\sim 10^{14}$ gauss, which would be formed during the compression of matter which forms the neutron star. This compression occurs during the hydrodynamic collapse of a pre-supernova star. Colgate and White[9] have found that a degenerate neutron core starts to build up in such a collapse, and additional matter descending on this core releases large amounts of gravitational potential energy. The deposition of this energy forms a strong shock wave which ejects the outer layers of the star. We must expect that the internal magnetic lines of force would be drawn radially outward in this explosion. However, the rotation of the remaining neutron star would twist the lines of force in the inner region so that they would have to reconnect to form a self-contained magnetosphere.

The surface temperature of a neutron star is comparable with the kinetic temperature in the solar corona, but its radius is orders of magnitude less than that of the Sun. Hence the stellar wind associated with a neutron star will be negligibly small compared with the solar wind, according to the hydrodynamic model for coronal expansion[10], unless much higher kinetic temperatures are produced in a corona around the neutron star. It should not be ruled out that the mechanism to be discussed here might produce these higher kinetic temperatures, in which case there could also be a bremsstrahlung component in the X-ray emission. The heating of the solar corona appears to be produced by generation of acoustic, gravity and hydromagnetic waves by turbulence in the convective layers below the solar photosphere. It is clear that no similar convective region can exist in a neutron star[6].

However, the neutron star is capable of storing gravitational potential energy in the form of radial oscillations. Such oscillations will have a period in the millisecond range (F. J. Dyson, personal communication). The shock wave which ejects matter in the supernova explosion will eject only the outer layers; the inner layers will be accelerated outward by the shock but will fall back on to the neutron star. It seems likely that a substantial amount of energy may thus be stored in the resulting radial oscillations. The gravitational binding energy of a neutron star is a sensitive function of the mass[6], but it may typically amount to several per cent of the rest mass energy. Hence it may be possible to store $\sim 10^{52}$ ergs as vibrational energy in such a star. This is 5 or 6 orders of magnitude greater than the thermal energy content of a neutron star at the end of the initial rapid neutrino cooling stage[6].

The radial oscillations will generate hydromagnetic waves at parts of the magnetic field which emerge from the photosphere at some angle to the normal. These waves will traverse the magnetosphere and can accelerate electrons. If this picture holds for the Crab Nebula, then evidently the electrons escape from the magnetosphere into the radial magnetic field system of the surrounding expanding envelope. The electrons will initially emit X-rays by the synchrotron process, but their synchrotron lifetime for X-ray emission is only about one year[8]. This would account for the observation that the region of X-ray emission in the Crab Nebula is smaller than the region of optical synchrotron emission.

If these considerations are correct, it is evident that many other non-thermal phenomena will be associated with the mechanical energy of vibration of neutron stars, and hence that extensive theoretical investigations of such phenomena may be rewarding.

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