

# **Neutron stars and cosmic-ray production**

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Recent investigations of the properties of neutron stars and of supernova explosions indicate that neutron stars should frequently be formed as supernova remnants. It now appears unlikely that any form of internal energy storage can play an important role in the production of X rays or cosmic rays. If mass infall onto a neutron star occurs at the upper limiting value allowed by radiation stresses, instabilities are likely to make the resulting mass infall, X-ray, gamma-ray, and cosmic-ray production very intermittent. It is shown that such a model may be able to account for many features of the Crab nebula: the energy input in electrons and ions, the character of the fast-moving light ripples or wisps, and the strong point source of  $\sim 50$  MHz radiation.

## STATUS OF NEUTRON STAR THEORY

A great deal of progress has been made recently in understanding the basic processes which occur in supernova explosions as a result of various numerical hydrodynamic studies (Colgate and White 1966; Arnett 1966, 1967; Arnett and Cameron 1967; Truran, Arnett, Tsuruta, and Cameron 1967). These studies start with the collapse of a stellar model which loses its hydrostatic stability as a result of attainment of extreme values of central temperature or density. The collapse proceeds until central densities comparable to that of nuclear matter are reached, at which point the pressure becomes high enough to halt the collapse of the core material, and temperatures in the range  $10^{11}$ – $10^{12}$  °K are attained. Under these conditions the material becomes opaque to neutrinos and anti-neutrinos; these particles diffuse outwards, deposit energy in the infalling envelope, and cause the envelope to be ejected.

The remnant of the supernova explosion will become a neutron star unless its mass exceeds the upper limit for which such an object can be in hydrostatic equilibrium. The upper mass limit is a function of the nuclear

force contributions to the equation of state; Tsuruta and Cameron (1966*a*) found that it probably lies in the range one to two solar masses, and recent work on the properties of nuclear matter (Weiss and Cameron 1967) suggests that the higher of these two figures is probably the better value. The hydrodynamic studies indicate that there is at least a significant range of stellar mass in which the supernova remnant will not exceed two solar masses, and hence neutron stars should commonly be formed in such explosions.

Since the neutron star is formed as a result of a dynamically violent compressional event, in principle large amounts of energy ( $10^{51}$  or  $10^{52}$  ergs) can initially be stored in thermal, vibrational, rotational, or magnetic form. It has been interesting to consider whether any significant amounts of these forms of energy can be channelled into the production of X rays or cosmic rays (Cameron 1965*a, b*). It appears that the thermal energy content diminishes rapidly (Tsuruta and Cameron 1966*b*), that the rotational energy is probably lost quite abruptly (Tsuruta and Cameron 1966*c*), and that the vibrational energy is relatively rapidly dissipated by neutrino emission (Hansen 1966) and by hydrodynamic shocks (Mock 1967). Hence it does not appear very promising to postulate that significant amounts of energy can be channelled

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into X-ray emission or cosmic-ray production from neutron stars as old as the Crab nebula.

#### MASS INFALL ON NEUTRON STARS

Shklovsky (1967) has recently suggested that the characteristics of the Scorpius X-ray source can be explained by a model in which a neutron star accretes mass from a binary companion. The steady accretion of mass onto neutron stars and white dwarf stars has been analyzed (Cameron and Mock 1967), and it has been concluded that the Scorpius source is consistent with mass accretion onto a white dwarf star rather than onto a neutron star. The analysis indicated that steady mass accretion onto a neutron star should produce thin-source bremsstrahlung at a temperature of the order of  $2 \times 10^{10}$  °K, which would constitute a gamma-ray source, and thermal radiation at a temperature of about  $10^7$  °K, which would constitute an X-ray source.

In this paper we consider mass accretion onto a neutron star in the limit imposed by the radiation stress. We believe that many features of the Crab nebula can be explained by such a model, and these are discussed.

If the radiation emitted by a star becomes sufficiently intense, the stress exerted on surrounding material may exceed gravity. If this radiation results from the release of gravitational potential energy by infalling material, then the radiation stress gives an upper limit to the rate of infall and the resulting luminosity (Colgate and White 1966):

$$(1) \quad \frac{N_0 \sigma_c L}{\mu_e c 4\pi R^2} \approx \frac{GM}{R^2},$$

where  $N_0$  is Avogadro's number,  $\mu_e$  is the mean mass number per electron,  $\sigma_c$  is the Compton scattering cross section,  $L$  is the luminosity, and  $M$  is the mass of the star of radius  $R$ . It may be noted that this upper limit on  $L$  is independent of the radius. However, the mass flux does depend on the radius:

$$(2) \quad F = RL/GM.$$

As typical neutron star parameters we may take  $M = 2 \times 10^{33}$  g = 1 solar mass and  $R = 10^6$  cm. The infalling material is likely to have  $\mu_e \approx 4/3$  if it still contains much hydrogen. Half the high-temperature thin-source bremsstrahlung will be absorbed and

reemitted in the X-ray region by the photosphere; consequently  $\sigma_c$  should not be taken too much below the Thomson scattering cross section. We adopt  $\sigma_c \approx 4 \times 10^{-25}$  cm<sup>2</sup>. This gives

$$L \leq 2.8 \times 10^{38} \text{ ergs/s.}$$

The mass flux required to give the maximum luminosity is  $2.1 \times 10^{18}$  g/s.

We emphasize that these numbers refer to a steady-state condition. However, the limiting rate of infall represents at best a state of neutral stability. If a perturbation occurs which allows an extra blob of matter to fall toward the neutron star, then when that blob strikes the star and radiates its energy into space, the luminosity will increase above the limiting value, thus giving the other infalling material a radiation stress impulse which will cause it to recede from the star temporarily. This will cut off the radiation, leaving the external material free to fall toward the star until the next blob arrives and causes another temporary recession. Thus the limiting luminosity and mass flux refer only to the time average of the infall of material onto a neutron star: it is evident that the actual behavior is likely to be much more intermittent. For example, if the time interval between the arrival of blobs of material should be  $\sim 10^7$  s, then the neutron star would radiate  $\sim 10^{45}$  ergs in each of the X-ray and gamma-ray ranges during an interval of a few seconds a few times a year. The detection of such phenomena would require continuous monitoring with space instrumentation.

A similar intermittent phenomenon should not be expected in the case of mass infall at the radiation stress limit onto a white dwarf star. In that case (Cameron and Mock 1967) a large portion of the gravitational potential energy is released below the photosphere, so that there is a time lag in the radiation which will serve to smooth out the infall rate.

When a blob of matter arrives at the neutron star surface and is halted, the released gravitational energy creates a very high gas kinetic temperature:

$$(3) \quad T = \frac{2 GM\mu}{3 N_0 k R},$$

where  $\mu$  is the mean molecular weight (about

$2/3$  if the infalling material has solar composition) and  $k$  is Boltzmann's constant. For our typical parameters,  $T \approx 7 \times 10^{11}$  °K. It should be noted that the mean thermal energy thus corresponds to escape velocity.

There are numerous efficient mechanisms likely to accelerate the more energetic particles to still higher energies (Tsytovich 1966). Plasma waves can accelerate the electrons. If the electron temperature becomes higher than the ion temperature, as is likely, then ion acoustic waves can accelerate the ions. If the infalling material has compressed a magnetic field to  $\geq 10^8$  gauss, then relativistic hydromagnetic waves will be very efficient in accelerating particles. In these various waves a significant fraction of the total energy release is likely to go into the creation of a high-energy relativistic plasma.

This plasma will expand away from the neutron star and escape into the surrounding ejected envelope. In so doing it will exert a pressure on the infalling gas that reinforces the radiation stress impulse which turns back this material. However, this pressure will not affect more than the innermost material. The relativistic plasma will be of lower density than the infalling gas, and hence a Rayleigh-Taylor instability will exist which will form the infalling gas into flutes between which the relativistic plasma will escape. These flutes will constitute the gas blobs which were referred to above. We expect that the flutes will be quite irregular, and hence the time intervals between successive X-ray and gamma-ray outbursts should be quite variable.

#### THE CRAB NEBULA

Let us now apply these ideas to the Crab nebula. This object is one of the most unusual supernova remnants that has been studied, owing to its extremely high luminosity in most wavelength ranges from the radio to the X-ray regions. It may be estimated (Shklovsky 1966; Melrose 1967) that  $10^{37}$  or  $10^{38}$  ergs/s must be input into relativistic electrons to account for the synchrotron emission. A comparable energy input would be required to offset the energy loss by expansion of the Crab (Melrose 1967). It is noteworthy that this energy input approaches the maximum energy release obtainable from mass infall onto a

neutron star. It is certainly compatible with the fraction of that energy release which can go into particle acceleration.

One of the very interesting features of the Crab is the appearance three or four times a year of light ripples, or wisps (Oort and Walraven 1956; Woltjer 1958). These are approximately elliptical regions of enhanced radiation with 90% polarization, indicating that the enhanced radiation is due to the synchrotron mechanism. The magnetic field lies along the major axis of the ellipse, and the ellipse moves in the direction of the minor axis with a velocity of  $\sim 0.1c$ .

We interpret these as hydromagnetic waves propagating in the suprathermal gas in a direction nearly perpendicular to the field lines (Parker 1965). From the velocity of propagation of  $0.1c$  we deduce that the energy density in the relativistic gas is  $\sim 10^7 n$  eV/cm<sup>3</sup>, where  $n$  is the number density of thermal electrons. From the observed acceleration of the expanding shell the energy density in the suprathermal gas is unlikely to be greater than  $10^5$  eV/cm<sup>3</sup>. Since the energy density in relativistic electrons required to give the synchrotron emission is  $\sim 10^4$ – $10^5$  eV/cm<sup>3</sup>, we conclude that the energy density in accelerated ions is not substantially greater than that in electrons, and the number density of thermal particles can be of the same order as that of suprathermal particles. However, substantial acceleration of ions can have taken place.

It is natural to suggest that the wisp hydromagnetic waves are excited by the intermittent infall of blobs of gas onto a neutron star, as discussed above. This process can also be expected to accelerate particles at about the right rate.

There is a strong point source of  $\sim 50$  Mhz radiation in the Crab (Hewish and Okoye 1965; Bell and Hewish 1967). If we attribute this to conversion of plasma oscillations to electromagnetic radiation (Shklovsky 1966), electron densities  $\sim 10^7$  cm<sup>-3</sup> are required. Such densities can be expected inside a radial distance of  $10^{14}$  cm for matter free-falling onto a neutron star at the radiation stress limit. This distance is an order of magnitude larger than the amplitude of radial oscillation of the innermost gas blobs between outbursts. Actually it is claimed that the source has a

radius  $\sim 2 \times 10^{15}$  cm (Bell and Hewish 1967). If the material falls in a reduced effective gravity (corresponding to  $G_{\text{eff}} \sim 0.2$  G) because of the presence of radiation, then electron densities  $\sim 10^7$  cm $^{-3}$  will extend to distances  $\sim 2 \times 10^{15}$  cm.

If matter has been falling into a Crab neutron star at the radiation stress limit for its age of  $3 \times 10^{10}$  s, the total mass accumulated is  $\sim 6 \times 10^{28}$  g, or  $3 \times 10^{-5}$  solar masses. This small amount of mass can probably be obtained very easily from the envelope ejected in the supernova explosion as a result of pressure equalization in the nebular interior. All other supernova envelopes are observed to expand much faster than the Crab nebula, which may account for their failure to exhibit most of the spectacular phenomena observed in the Crab.

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