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A model for LSI 61° 303

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Summary. The radio star LSI 61° 303 is an unusual object possibly associated with the γ-ray source CG 135. The recently observed radio periodicity of 26 day strongly suggests that the system is a binary. Here we propose that the invisible companion is a relatively young pulsar (of age 10^4–10^5 yr) losing energy via a relativistic wind. At the boundary between the pulsar wind and the stellar wind of the primary, the dominant energy-loss for relativistic electrons is Compton-scattering off the optical photons of the primary, which should account for the X-ray to γ-ray emission, while synchrotron radiation from the same electrons would explain the radio emission. If the source radiates 10^{37} erg s^{-1} in the MeV band, as suggested by the observations by Perotti *et al.*, a very high efficiency of production of 1-GeV electrons by the pulsar is required, which agrees with the expectations of some pulsar models. A substantial orbital eccentricity is expected.

1 Introduction

The discovery of an unusually variable non-thermal radio source associated with the star LSI 61° 303 has suggested this object as the possible counterpart of the gamma-ray source CG135 (Gregory & Taylor 1978; Gregory *et al.* 1979). While the alternative association of the γ-ray source with the QSO 0241 +60 (Apparao *et al.* 1978; Worrall *et al.* 1981) cannot be dismissed, the recent report of a 26.5-day periodicity in the radio emission of LSI 61° 303 (Taylor & Gregory 1980) leads us to consider in detail the first possibility.

Interpreting the observed period as a binary period, we propose that the secondary star is a moderately young pulsar (10^4–10^5 yr). The basic assumption is that a pulsar loses its rotational energy via a 'relativistic wind' (electromagnetic waves, relativistic particles) as suggested by Rees & Gunn (1974) for explaining the activity around the Crab Nebula pulsar. In the shock, generated at the boundary between the relativistic wind and the wind of the primary star, the power can be radiated in various frequency bands with efficiencies depending on the physical parameters of the shock region, which is determined by the balance of the ram pressure of the matter with that of the relativistic wind.

We estimate these parameters in the case of LSI 61° 303, and find that the most plausible mechanism of X- and γ-ray production is Compton-scattering of relativistic electrons generated by the pulsar, off the optical photons of the primary.

2 Observational features of LSI 61° 303

Optical observations of LSI +61° 303 (Gregory *et al.* 1979) suggest a spectral type B0 with an absolute magnitude $M_V = -4.3$ ($L = 10^{38}$ erg s^{-1}), corresponding to a mass between 10 and 20 $M_\odot$ and a radius of 10 $R_\odot$. Far-ultraviolet observations show a complex continuum and emission lines indicating a high mass loss, and possibly a higher luminosity ($M_V = -6$, $L \simeq 10^{39}$ erg s^{-1}) than derived from the optical data (Hutchings 1980). The distance is estimated to be 2.3 kpc on the basis of absorption and comparison with the nearby HII region IC 1805. If the period observed in the radio emission is the orbital period, the amplitude of variation of the radial velocities of the optical lines (which has not yet been shown to be periodic) indicates a secondary mass of 1–1.9 $M_\odot$ for an inclination angle $\geqslant 60°$, as suggested by the absence of optical modulation. For a total mass of 15 $M_\odot$, the separation of the system is $D = 6.6 \times 10^{12}$ cm.

An X-ray source at the location of LSI 61° 303 (20 × 30 arcmin positional uncertainty) was observed by Share (1979) with *HEAO-1*, yielding a luminosity $\simeq 10^{33}$ erg s^{-1}. The identification of the X-ray source with the radio star LSI 61° 303 was confirmed by *Einstein* observations (Bignami *et al.* 1980). At higher energies the situation is unclear because of the confusion with the QSO 0241+60 which is only 1° away. Observations by *OSO7* with an error box of 0°.5 × 3°.5, indicated a hard spectrum with an energy index $\alpha \simeq 0$ (Maraschi *et al.* 1978). The corresponding X-ray luminosity in the 1–40 keV range is 10^{35} erg s^{-1}. At energies of tenths of keV, the upper limits derived by *OSO8* (Worrall *et al.* 1981) indicate a possible variability of the X-ray intensity. Emission in the energy range 0.1–1 MeV with a positional uncertainty of 1°.5 × 6° has also been reported (Coe, Quenby & Engel 1978; Perotti *et al.* 1980). If this is associated with LSI +61° 303, the corresponding luminosity is $L(0.1\text{–}1\,\text{MeV}) \simeq 10^{37}$ erg s^{-1}. The luminosity above 100 MeV derived from the *COS-B* data is $L(100\,\text{MeV}) \simeq 10^{35}$ erg s^{-1} (Wills *et al.* 1980).

3 The model

The assumed pulsar power is $P = 10^{36}\text{–}10^{37}$ erg s^{-1}, the higher value being required if the observed 1–10 MeV flux is to be associated with LSI +61° 303. Assuming the usual formula for the pulsar energy loss we have

$$P \simeq 6 \times 10^{31} a_6^6 B_{s12}^2 T_s^{-4} \text{ erg s}^{-1}, \tag{1}$$

where T_s is the spin period in seconds, B_{s12} the surface magnetic field in units of 10^{12} G and a_6 the radius of the neutron star in units of 10^6 cm. $P = 10^{36}\text{–}10^{37}$ implies a period $5 \times 10^{-2}\text{–}10^{-1}$ s for standard neutron star parameters ($a_6 \simeq 1$, $B_{s12} \simeq 1$) and an age of $10^4\text{–}10^5$ yr.

Pulsar models predict that a substantial fraction of the energy loss is in the form of high-energy particles and low-frequency electromagnetic radiation. The boundary r_b of the region dominated by this 'relativistic wind' is determined by a balance condition with the external pressure due to the wind of the primary

$$\frac{\dot{M}V}{4\pi(D-r_b)^2} = \frac{P}{4\pi c r_b^2}, \tag{2}$$

where $\dot{M}$ is the mass loss of the primary and V the terminal velocity of its wind.

We shall take $V = 10^8 V_8$ cm s^{-1} and $\dot{M} = 10^{-7} \dot{M}_{-7} M_\odot$ yr^{-1}. The latter value is larger than the average mass loss for a luminosity $\simeq 10^{38}$ erg s^{-1} but reasonable for this object in view of the observed P Cygni profiles in the ultraviolet lines. This gives

$$r_b = \frac{\beta}{1+\beta} D$$

where (3)

$$\beta = \frac{1}{2} \frac{P_{37}}{V_8 \dot{M}_{-7}}$$

and for $P_{37} \simeq V \simeq \dot{M}_{-7} \simeq 1$, $r_b = 0.42D = 2.7 \times 10^{12}$ cm. The anisotropy of both pressures has been neglected. This approximation should be sufficient for order of magnitude estimates, at least for the region of the boundary between the two stars. A shock will form at this boundary, behind which the relativistic wind is randomized.

Supposing that the magnetic field in the pulsar wind decays as $(1/r)$ from its value at the speed of light cylinder, one has

$$B = B_s \frac{a^3}{c^2} \frac{4\pi^2}{T_s^2} r^{-1} \tag{4}$$

and, at the boundary, $B(r_b) = 6$G so that the magnetic energy density $W_B = 1.6 \,\text{erg cm}^{-3}$, and the kinetic energy density of the wind of the primary, $W_k = 3.6 \,\text{erg cm}^{-3}$, are comparable.

Provided $\beta < 1$, these values are independent of the spin period T_s, since r_b adjusts, varying approximately as T_s^{-2}. The energy density of photons emitted by the primary is $W_{ph} = L/4\pi(D - r_b)^2 c = 10 \,\text{erg cm}^{-3}$.

High-energy particles are accelerated at the pulsar surface and at the boundary where the electromagnetic field interacts with the external plasma. In any case, the particles originating from the pulsar should not radiate after leaving the speed-of-light radius as indicated by the optical and X-ray brightness distributions around the Crab Pulsar. At the boundary, radiation processes become important.

Compton-scattered photons with energy E_c derive from electrons with Lorentz factor $\gamma = [3/4(E_c/\bar{\epsilon})]^{1/2}$. Since in our case $\bar{\epsilon} \simeq 3$ eV, values of γ in the range 30–10^4 are required to explain the X- to γ-ray emission. With the photon energy-density given above, the lifetime for Compton losses is

$$t_c \simeq 6 \times 10^6 \gamma^{-1} \text{ s.} \tag{5}$$

Therefore, for the relevant particles, t_c is between 2×10^5 and 6×10^2 s. In order that the radiation efficiency in the MeV range be close to one, the confinement time in the region of scale r_b should be larger than 5×10^3 s, implying a drift velocity of the relativistic particles $\lesssim 5 \times 10^8 \,\text{cm s}^{-1}$.

If the reported γ-ray fluxes (Wills *et al.* 1980; Perotti *et al.* 1980) are actually due to LSI 61° 303, one must require that electrons with energy 1 GeV are accelerated by the pulsar with maximum efficiency, which compares well with the expectations of the class of pulsar models proposed by Arons (1980). On the other hand it is clear that, if the X-ray to γ-ray spectrum were steeper, the demands on the model would only be less stringent.

Synchrotron radiation from the same electrons responsible for the X- and γ-ray emission should account for the radio emission. With the usual formulae, and assuming for the radiation a spectral index $\alpha \simeq 0$, we find that the effective field in a region of dimension r_b should be $\simeq 0.3$ G. This is significantly smaller than the field at the boundary, but much larger than that carried by the stellar wind. It could be considered as an average value, if the boundary field decays on a length-scale of a fraction of r_b.

Thermal radiation from the plasma heated by the dissipative processes beyond the shock is not important, because of the low density $n = 3 \times 10^8 \, \mathrm{cm}^{-3}$. In fact $L_{\mathrm{ff}} \simeq 10^{29} T_8^{1/2} \, \mathrm{erg \, s^{-1}}$.

Protons may be accelereated together with electrons. Their nuclear interaction time in the surrounding plasma, whose density is $4 \times 10^8 \, \mathrm{cm}^{-3}$, is $t_{\mathrm{p}} = 4 \times 10^7 \, \mathrm{s}$. Therefore a negligible fraction of their power should be converted into γ-rays near the two stars.

4 Discussion

We have shown that, if LSI+61° 303 is part of a binary system with a moderately young pulsar as a companion ($P = 10^{37} \, \mathrm{erg \, s^{-1}}$, $T_{\mathrm{s}} = 5 \times 10^{-2} \, \mathrm{s}$, $t = 10^4 \, \mathrm{yr}$), the observed radio and X-ray emission can be accounted for. The γ-ray emission can be explained, provided that a substantial fraction of the rotational energy loss of the pulsar appears in the form of 1-GeV electrons. This fraction should be close to 1 if the system is a steady soft γ-ray source at the flux level reported by Perotti *et al.* (1980).

The presence of a shock boundary around the pulsar should greatly enhance the conversion of the pulsar power into high-frequency radiation with respect to the case of isolated pulsars like the Crab or Vela pulsars. Depending on the luminosity of the primary and on the separation of the system, the dominant emission mechanism will be Compton scattering, as in the case examined here, or synchrotron radiation and π^0 decay plus thermal radiation as in the case of Cyg X-3 (Bignami, Maraschi & Treves 1977). Models involving pulsars in binary systems have also been considered for Cir X-1 and SS 433 (e.g. Begelman *et al.* 1980; Fabian 1980; Maraschi & Treves 1980).

Observationally, the common feature of these systems is the strong radio emission, and the models suggest that they should contain young neutron stars (of age 10^3–10^4 yr). Only in one case, SS 433, is the remnant of the supernova explosion which gave birth to the pulsar probably observed. In another case, Cir X-1, the association with a remnant is dubious. On the other hand, the large eccentricities invoked to explain the asymmetries in the light curves of Cyg X-3 and Cir X-1 (Elsner *et al.* 1980; Molteni *et al.* 1980; Maraschi & Treves 1980) would, if confirmed, provide direct evidence of the young ages of these systems, and at the same time imply the possibility of neutron star formation with very short-lived (10^3 yr) remnants.

By analogy, we would expect also in the case of LSI+61°303 a substantial eccentricity, which in this case could be unambiguously derived from radial-velocity observations.

The number of binaries containing neutron stars with $t \lesssim 10^4$ yr, derived from Van den Heuvel's (1978) estimates, is $\simeq 0.5$ within 3 kpc and $\simeq 10$ in the whole galaxy (Maraschi & Treves 1979). Note, however, that the γ-ray sources detected by *COS-B* could be accounted for with pulsars of power $\simeq 10^{36} \, \mathrm{erg \, s^{-1}}$, implying ages of the order of 10^5 yr. If the efficiency of production of γ-rays is large, as we have argued in this paper, it is possible that other γ-ray sources are middle-aged pulsars in binaries.

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