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Is the X-ray pulsar H 0253+193 a neutron star spun down in a molecular cloud?

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Abstract. The detection of 206 s X-ray pulsations from H 0253+193 indicates that the source is a compact object. It is argued here that the object can not be a T Tauri star or a Be/X-ray binary pulsar embedded in the molecular cloud L 1457. It is suggested that H 0253+193 is a slowly rotating single neutron star now accreting interstellar matter after having been spun down by a propeller type mechanism during its passage through the cloud.

Key words: X-ray pulsars – propeller spin down – interstellar medium: clouds – accretion

1. Introduction

The HEAO A-2 hard X-ray source H 0253+193 (Marshall et al., 1979) is a high galactic latitude object ($l = 159°$, $b = 34°$). Halpern and Patterson (1987) found its position (obtained with the Einstein Observatory imaging proportional counter) to coincide with the peak in the CO map of the molecular cloud MBM 12 (Magnami et al., 1985). MBM 12 is identical to the dark cloud L 1457 in the Lynds (1962) catalogue. Hobbs et al. (1986) have determined a distance of 65 pc for this cloud by mapping the interstellar Na I D absorption toward several stars at different distances in its neighbourhood. Halpern and Patterson (1987) suggested that H 0253+193 is likely to be a T Tauri star embedded in the molecular cloud L 1457. However, there is no optical counterpart to a limiting magnitude of about 20 and there is no IRAS point source at the X-ray source position.

Takano et al. (1989) have reported the discovery of X-ray pulsations from H 0253+193. The pulse period is 206 s. The average 2–20 keV X-ray intensity F_x is $6\ 10^{-11}$ erg cm^{-2} s^{-1}. If the X-ray source is embedded within the core of the molecular cloud L 1457 at a distance "d" of 65 pc the X-ray luminosity L_x ($= 4\pi d^2 F_x$) of H 0253+193 is $\sim 3\ 10^{31}$ erg s^{-1}. A large column density ($2\ 10^{22}$ cm^{-2} $< N_{\rm H} <$ $1.5\ 10^{23}$ cm^{-2}) and hence high visual extinction ($A_v > 10$) to the X-ray source was derived from the CO and X-ray data (Magnami et al., 1985; Halpern and Patterson, 1987).

X-ray pulsations at a period of 206 s strongly suggest the presence of a compact object. Here we consider two possibilities. In the first the X-ray pulsar is in a binary system similar to other Be/X-ray binary pulsars (see e.g. Van den Heuvel, 1981). In the second the object is a single slowly rotating neutron star, now accreting interstellar matter after having been spun down by a propeller type mechanism in the interstellar medium. In view mainly of the presence of X-ray pulsations and also the absence of any infrared counterpart it seems unlikely that H 0253+193 is a T Tauri star embedded in the core of L 1457. The bolometric luminosity of T Tauri stars is about 10^3 times their X-ray luminosity (Feigelson and De Campli, 1981) and is mainly emitted in the infrared (see e.g. Cohen et al., 1989). If H 0253+193 were a dust enshrouded T Tauri star as close as 65 pc (the distance of L 1457) it would be a strong infrared source ($L_{\rm IR} \sim 10^{34}$ erg s^{-1}). However, there is no IRAS point source at the X-ray source position.

2. The Be/X-ray binary model

The X-ray pulse period (P) of H 0253+193 is similar to other long period ($P > 100$ s) X-ray pulsars in Be/X-ray binary systems that consist of a neutron star and an emission line OB type star earlier than B 2 Ve type (Rappaport and Van den Heuvel, 1982; Van den Heuvel and Rappaport, 1987). However, such a Be/X-ray binary could not be embedded in the dark cloud L 1457. An OB star earlier than B 2 Ve has an absolute magnitude $M_v \lesssim -2.2$ (Habets and Heintze, 1981). While a high visual extinction ($A_v > 18$) due to dust in the cloud (at a distance of 65 pc) can make the apparent magnitude of the object fainter than $V \sim 20$ to be consistent with the absence of any optical counterpart, the absence of any infrared counterpart will be hard to explain. The absorbing dust in the cloud would be heated by the stellar radiation from the OB type star and reemit in the infrared so that the object would become a strong infrared source, contrary to what is observed.

The Be/X-ray binary pulsar could be behind the cloud L 1457. But, it could not be much farther than about 200 pc because the scale height of early OB type stars from the galactic plane is $\sim$50–60 pc (Allen, 1973) and the galactic latitude of H 0253+193 is $-34°$. For a distance $d = 200$ pc (height from the galactic plane $\sim$120 pc and the X-ray luminosity $L_x \sim 10^{32}$ erg s^{-1}) the OB (earlier than B 2 Ve) type component in the object H 0253+193 must suffer an extinction $A_v \gtrsim 16$ for it to become fainter than $V \sim 20$. In this case there is no infrared emission due to heated circumstellar dust, but it should be possible to detect the early type star in the infrared due to its stellar radiation and much lower extinction in the infrared. For example, for $A_v = 16$ the extinction at the wavelength $\lambda = 2.2$ μm (the K band) $A_{\rm K} = 2$ for normal interstellar extinction (Savage and Mathis, 1979). For a B 2 V star with radius $R = 3.3\ 10^{11}$ cm and effective temperature $T_{\rm eff} = 2.23\ 10^4$ K (Habets and Heintze, 1981) at a distance 200 pc suffering this much extinction, the expected magnitude in the 2.2 μm band $K = 6.4$ for an assumed black body emission. In the IRAS 12 μm band a flux density $\sim$0.4 Jy is expected, which is well within the IRAS sensitivity. In fact, the Be stars have infrared excesses (Coté and Waters, 1987; Waters et al., 1987), so that these values are lower limits to the expected infrared brightness. As an example, consider the B 2 Ve star 105 Tau which for $V=5.89$, $B-V=0.19$ and $E(B-V)=0.43$ is at a distance $d \simeq 225$ pc and has an IRAS flux density $F_{12\,\mu\mathrm{m}}=1.47$ Jy (Coté and Waters, 1987; Waters et al., 1987). Thus, it seems unlikely that H 0253+193 is a Be/X-ray binary system less distant than about 200 pc.

3. Single accreting neutron star model

H 0253+193 may be a single neutron star accreting from the interstellar medium. For a neutron star of mass M_* and radius R_* moving with velocity V_* through the interstellar medium of density ϱ, the accretion rate $\dot{M}$ is given by

$$\dot{M}=\pi(2\,GM_*/V_*^2)^2\,V_*\varrho\,, \tag{1}$$

where G is the gravitational constant and $(2\,GM_*/V_*^2)=r_a$ is the accretion radius (Hoyle and Lyttleton, 1939). This is valid only if the neutron star motion is supersonic. In a general case V_* should be replaced by $(V_*^2+V_s^2)^{1/2}$ where V_s is the sound speed in the interstellar gas, which may in turn be modified by the X-rays from the accreting star. The density $\varrho=\mathrm{nm}$ where n is the number density of hydrogen atoms and $m=2.3\ 10^{-24}$ g assuming 10% of the atoms to be helium. For typical values of different parameters, the accretion rate $\dot{M}\simeq 5\ 10^{11}\ (M_*/M_\odot)^2\ (V_*/10\,\mathrm{km\,s^{-1}})^{-3}$ $(n/\mathrm{cm^{-3}})\ \mathrm{gs^{-1}}$. The gravitational potential energy released upon accretion gives rise to an accretion luminosity $L_x=GM_*\dot{M}/R_*\simeq 6.9\times 10^{31}\,m_*^3\,V_{*6}^{-3}\,n\,R_{*6}^{-1}\,\mathrm{erg\,s^{-1}}$, where $m_*=(M_*/M_\odot)$, $V_{*6}=(V_*/10^6\,\mathrm{cm\,s^{-1}})$, $R_{*6}=(R_*/10^6\,\mathrm{cm})$ and n is in units of $\mathrm{cm^{-3}}$. If this energy were to be emitted as blackbody radiation ($L_x=4\pi\,R_*^2\,\sigma\,T^4$, where σ is the Stefan-Boltzmann constant and T is the temperature) the effective kT (where k is the Boltzmann constant) would be ~ 0.1 keV. However, at such low accretion rates the emitted spectrum in the presence of strong magnetic fields (field strength $B\sim 10^{12}$ Gauss) will be highly nonthermal. Electron cyclotron emission may be the dominant energy loss mechanism in which case the emitted spectrum will fall in the hard X-ray range, as the cyclotron energy $h\nu_c\ (=heB/2\pi m_e c$, where $\nu_c=eB/2\pi m_e c$ is the electron cyclotron frequency in a magnetic field of strength B, h is the Planck constant, e the electric charge and m_e the mass of electron and c is the speed of light) $\simeq 12$ keV for a neutron star surface magnetic field $B\sim 10^{12}$ Gauss.

The observed X-ray pulse period (206 s) is, however, rather too long for an isolated neutron star. For example, the radio pulsars have periods $\lesssim 1$ s. A mechanism must be found to spin down the neutron star in H 0253+193 in the interstellar medium. The process of spin down of magnetized neutron stars in binary systems has been discussed by various authors (e.g. Davidson and Ostriker, 1973; Shakura, 1975; Illarinov and Sunyaev, 1975; Lipunov and Shakura, 1976; Kundt, 1976; Holloway et al., 1978; Davies and Pringle, 1981). First, the neutron star born as a pulsar with spin period $\ll 1$ s spins down by the standard pulsar emission mechanism in which rotational energy is lost from the rotating magnetic dipole. The pulsar luminosity $L=2\,\mu^2\,(2\pi/P)^4\,c^{-3}/3$ (Ostriker and Gunn, 1971) and the time required to spin down to period P ($\gg$ initial period P_i) is

$$\tau_P=3\,c^3\,IP^2\,(1-P_i^2/P^2)/16\pi^2\mu^2\simeq 3\,c^3\,IP^2/16\,\pi^2\mu^2\,, \tag{2}$$

where $I\,(\simeq 10^{45}\,\mathrm{g\,cm^2})$ is the moment of inertia of the neutron star and $\mu=B_*\,R_*^3\,(\simeq 10^{30}\,\mathrm{Gauss\,cm^3})$ is the magnetic dipole moment of the neutron star that has a surface magnetic field strength B_*. For typical values of the parameters $\tau_P=1.7\ 10^7\ I_{45}\ \mu_{30}^{-2}\,P^2$ yr where $I_{45}=(I/10^{45}\,\mathrm{g\,cm^2})$ and $\mu_{30}=(\mu/10^{30}\,\mathrm{Gauss\,cm^3})$. This spin down by the pulsar mechanism continues until the pulsar radiation pressure at the accretion radius r_a $(=L/4\pi\ r_a^2\ c)$ falls below the gas pressure $(\sim\varrho v_*^2)$ there. This happens when $P>\{2\pi^3\,v_*^2\,\mu^2/\varrho^3\,c^4\,GM_*)^2\}^{1/4}\,\mathrm{s}\simeq 5\,\mu_{30}^{1/2}\,v_{*6}^{1/2}\,m_*^{-1/2}\,n^{-1/4}$ s. This requires a slow down time $\tau_P\simeq 4\ 10^8\,I_{45}\,\mu_{30}^{-1}\,v_{*6}\,m_*^{-1}\,n^{-1/2}$ yr. But in a time of this order the neutron star will have passed through clouds of higher densities. For example, in about 10^7 yr it will have passed through a cloud with density $n\sim 10\,\mathrm{cm^{-3}}$ and in about 10^8 yr through a cloud with density $n\sim 10^2\,\mathrm{cm^{-3}}$ (see e.g. Talbot and Newman, 1977). As the gas pressure at the accretion radius exceeds the pulsar radiation pressure, the pulsar emission is suppressed. Captured matter falls inward. The infall is arrested at the magnetopause (where magnetic pressure balances the gas pressure) and matter is forced into corotation. If the corotation speed exceeds the local keplerian speed, matter is flung away carrying angular momentum with it. This results in a slow down of the neutron star rotation. A number of versions of this propeller mechanism operating in binary systems have been proposed (see references given above). The most efficient of these is the one proposed by Holloway et al. (1978) in which the gas particles in the weak stellar wind encountered by the neutron star are non-interacting. For a neutron star accreting interstellar gas, as is being considered here, this approximation is appropriate. Following Holloway et al. (1978) the breaking torque N in this case can be written as

$$N=\dot{M}_{\mathrm{in}}\,r_m^2\,\Omega\alpha\delta\,, \tag{3}$$

where $\Omega=2\pi/P$, $\dot{M}_{\mathrm{in}}$ is the mass infall rate, $r_m=(\gamma\mu^2/\Omega\,\dot{M}_{\mathrm{in}}\,\delta)^{1/5}$ is the magnetopause radius and α, δ, γ are dimensionless parameters of order unity. With $\dot{M}_{\mathrm{in}}=\pi\ (2\,GM_*/v_*^2)^2\ v_*\,\varrho$ the spin down torque, for typical numerical values of different quantities, becomes

$$N\simeq 3.2\ 10^{31}\,m_*^{6/5}\ v_{*6}^{-9/5}\ n^{3/5}\ \mu_{30}^{4/5}\ P^{-3/5}\ \alpha\delta^{3/5}\ \gamma^{2/5}\,\mathrm{g\,cm^2\,s^{-1}} \tag{4}$$

and the spin down time scale $\tau_s=I\Omega/N$ can be written as

$$\tau_s\simeq 3.4\ 10^6\,I_{45}\ \mu_{30}^{-4/5}\ m_*^{-6/5}\ v_{*6}^{9/5}\ n^{-3/5}\ (P/5\,\mathrm{s})^{-2/5}\ \xi\,\mathrm{yr}\,, \tag{5}$$

where $\xi=\alpha^{-1}\,\delta^{-3/5}\,\gamma^{-2/5}$.

The neutron star might have very recently passed through the cloud L 1457 that has a density $n\sim 10^3\,\mathrm{cm^{-3}}$. For $n=10^3\,\mathrm{cm^{-3}}$, the spin down time scale

$$\tau_s\simeq 4.8\ 10^4\,I_{45}\,\mu_{30}^{-4/5}\,m_*^{-6/5}\,v_{*6}^{9/5}\,(n/10^3\,\mathrm{cm^{-3}})^{-3/5}\,(P/5\,\mathrm{s})^{-2/5}\,\xi\,\mathrm{yr}\,. \tag{6}$$

The spin down by the propeller mechanism occurs on a time scale much shorter than the time scale for initial spin down by the standard pulsar mechanism. If the neutron star in H 0253+193 has been spun down by the propeller mechanism during its passage through the dense $(n\sim 10^3\,\mathrm{cm^{-3}})$ cloud L 1457 it should have been first spun down by the pulsar mechanism to a period $P_i\simeq 0.9\,\mu_{30}^{1/2}\,v_{*6}^{1/2}\,m_*^{-1/2}\,(n/10^3\,\mathrm{cm^{-3}})^{-1/4}$ s. This would have taken a time $\tau_i\simeq 1.3\ 10^7\,I_{45}\,\mu_{30}^{-2}$ yr before entering the cloud. Within the cloud, the propeller mechanism spins down the pulsar still further to the observed period $P_f=206$ s. The time taken for this follows from $d(I\Omega)/dt=N$ and Eq. (3) for N. The slow down to P_f requires a time τ_s given by

$$\tau_s\simeq 2.6\ 10^5\ I_{45}\ \mu_{30}^{-4/5}\ v_{*6}^{9/5}\ m_*^{-6/5}\ (n/10^3\,\mathrm{cm^{-3}})^{-3/5} \cdot\xi\,P_i^{-2/5}\ \{1-(P_i/P_f)^{2/5}\}\ \mathrm{yr} \tag{7}$$

which for $P_f = 206\,\mathrm{s}$ and $P_i = 0.9\,\mu_{30}^{1/2}\ v_{*6}^{1/2}\ m_*^{-1/2}\ (n/10^3\,\mathrm{cm}^{-3})^{-1/4}\,\mathrm{s}$ becomes

$$\tau_s \simeq 2.7\ 10^5\, I_{45}\, \mu_{30}^{-1}\, v_{*6}^{8/5}\, m_*^{-1}\, (n/10^3\,\mathrm{cm}^{-3})^{-1/2}\, \xi\ \mathrm{yr}\,. \qquad (8)$$

During a time τ_s the neutron star traverses a distance $v_*\,\tau_s \simeq 2.7\, I_{45}\, \mu_{30}^{-1}\, v_{*6}^{13/5}\, m_*^{-1}\, (n/10^3\,\mathrm{cm}^{-3})^{-1/2}\, \xi\,\mathrm{pc}$.

This is comparable to the size of L 1457.

4. Discussion

The spin down time scales depend on the neutron star magnetic moment "μ" and the density "n" of the medium through which it is passing, apart from a number of other parameters. Higher "μ" and higher "n" require smaller spin down time scales. On the other hand higher velocity neutron stars require longer spin down time scales. If the magnetic field of the neutron star does not decay with time, even a fast moving ($v_{*6} \sim 10$, i.e. $v_* \sim 100\,\mathrm{km\,s}^{-1}$) pulsar not encountering any dense cloud for rather long times can be spun down to large P values in the intercloud medium ($n \sim 1\,\mathrm{cm}^{-3}$) within a few 10^9 yr ($<$ the age of the galaxy). Slow moving pulsars require less time for spin down. For them spin down to long periods can be achieved even before the magnetic field has decayed (if it does decay on time scales $\sim 10^7$ yr). Consider a situation where $v_{*6} = 1$ and $\mu_{30} = 10$. In a few 10^7 yr the neutron star spins down to a period $P \sim 10$ s by the standard pulsar mechanism and encounters a cloud of density $n \sim 10\,\mathrm{cm}^{-3}$. The pulsar emission is suppressed and the propeller mechanism now spins down the neutron star further to long periods on a time scale $\sim 3\ 10^5$ yr. In the case of H 0253+193 it is possible that a slow moving ($V_* \sim 10\,\mathrm{km\,s}^{-1}$) pulsar was spun down by the pulsar mechanism in a time $\sim 10^7$ yr, which then passed through L 1457 that has a density $n \sim 10^3\,\mathrm{cm}^{-3}$ and was spun down to the observed period $P = 206$ s in a time $\sim 3\ 10^5$ yr. Now the neutron star, after passage through the cloud L 1457, is on the other side of the cloud from us and is accreting matter from the lower density interstellar medium. The large column density of hydrogen ($N_{\mathrm{H}} \sim 10^{22}$–$10^{23}\,\mathrm{cm}^{-2}$) is due to the line of sight passing through L 1457. The association of the X-ray source with the peak of the CO map of L 1457 even after the neutron star has left the cloud would require the neutron star to have had only a small proper motion relative to the cloud since then. This can result if the space velocity of the neutron star relative to the cloud is mainly radial. As the source lies within $\sim 5'$ of the cloud centre one requires the transverse fraction of the velocity to be $\lesssim 0.04$ if the distance travelled since the star was inside the cloud is 2.7 pc. The corresponding probability for this occurrence is $\lesssim 10^{-3}$. If the neutron star is within the cloud core its direction of motion is not so constrained, but Eq. (1) for the accretion rate together with the high density ($n \sim 10^3\,\mathrm{cm}^{-3}$) in the cloud core and the observed low luminosity ($L_x \simeq 3\ 10^{31}\,\mathrm{erg\,s}^{-1}$) requires the neutron star velocity V_* to be $\sim 100\,\mathrm{km\,s}^{-1}$. Equation (8) shows that a neutron star with $v_* \sim 100\,\mathrm{km\,s}^{-1}$ can not be spun down to the observed period $P = 206$ s within the cloud traversal time ($\sim 10^4$ yr for $v_* \sim 100\,\mathrm{km\,s}^{-1}$). Therefore, in this case the neutron star should have already been spun down elsewhere in the interstellar medium before entering L 1457. The time needed for spin down in this case $\sim 10^9$ yr and it is required that the neutron star magnetic field does not decay over such long time scales.

If spin down took place during passage through the cloud L 1457, it should be noted here that once the neutron star leaves the dense cloud the mass infall rate $\dot{M}_{\mathrm{in}}$ decreases, causing the magnetopause radius r_m to increase if the neutron star magnetic moment μ stays constant. If $r_m > r_\Omega = (GM_* P^2/4\pi^2)^{1/3}$, the corotation radius, defined as the radial distance from the neutron star at which the local keplerian speed is equal to the corotation speed, the propeller mechanism inhibits accretion and spin down continues. However, for spherical infall of matter partial accretion can take place even when $r_m > r_\Omega$. Matter that falls on to the magnetosphere within a distance r_Ω of the rotation axis (i.e. a fraction $\sim r_\Omega^2/r_m^2$ of the mass infall rate $\dot{M}_{\mathrm{in}}$) can be accreted (Fabian et al., 1976). Using appropriate values of the various parameters in the expressions for r_Ω and r_m, it turns out that up to $\sim 10\%$ of the infalling matter can be accreted.

5. Conclusions

The presence of X-ray pulsations with a period of 206 s in the X-rays from H 0253+193 and the absence of any IRAS point source counterparts can not be explained if the source were a T Tauri star. An accreting neutron star rotating with a period of 206 s is required. Long period X-ray pulsations are characteristic of X-ray pulsars in Be/X-ray binary systems. However, H 0253+193 can not be a Be/X-ray binary pulsar embedded within the cloud L 1457 because it would then be a strong IRAS source. A Be/X-ray pulsar behind the cloud L 1457 is possible. However, if the Be/X-ray binary is at a distance $\lesssim 120$ pc from the galactic plane (the scale height of OB type stars from the galactic plane being ~ 50–60 pc; Allen, 1973) its distance from us would be $\lesssim 200$ pc and the Be star in the system would still be a detectable IRAS source at 12 μm. Also it should be a bright near infrared (e.g. in the K band) source. If H 0253+193 is more distant than ~ 200 pc, then its height from the galactic plane would be anomalously large for an early B type star and it should be a runaway object. It may still be detectable in the near infrared. An alternative possibility is that H 0253+193 is a single accreting neutron star spun down in the interstellar medium by a propellar type mechanism. If the neutron star magnetic field does not decay, spin down can be achieved even within the less dense intercloud medium. If the neutron star has happended to encounter the dense cloud L 1457 early in its life (in time $\sim 10^7$ yr) rapid spin down by the propeller mechanism is achieved in a time much smaller than the magnetic field decay time scale ($\sim 10^7$ yr). H 0253+193 has in this case passed through L 1457 recently at a velocity $\sim 10\,\mathrm{km\,s}^{-1}$ and is now behind the cloud. It is desirable to perform deep CCD imaging and near infrared photometry of H 0253+193 to help constrain the possible models for this object. It may also be noted here that in view of the large population of old neutron stars in the galaxy there should be a substantial number of X-ray sources like H 0253+193 in the galaxy.

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