THE MAGNETIC FIELDS AND ORIGINAL SPINS OF BINARY AND RUNAWAY PULSARS

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Pulsing X-ray sources are believed to be the progenitors of binary and runaway pulsars. Thus, their observed properties and predicted fates furnish information about the initial properties and evolution of these pulsars. Evidence is discussed which suggests that many binary and runaway pulsars are born with periods $\sim$ seconds and dipole magnetic fields $\sim 10^{11} - 10^{13}$ G, and that the turnoff of at least some is not due to decay of their dipole magnetic fields.

1. INTRODUCTION

A majority of pulsars are believed to have been formed in close binary systems, and a significant fraction are believed to have once been accreting X-ray stars (see van den Heuvel 1981). The magnetic fields and spin evolution of accreting neutron stars therefore provide information about the magnetic fields and original spins of some pulsars. The magnetic fields of pulsing X-ray stars can be inferred from spectroscopic and timing studies, while their final spins can be predicted from the accretion flow pattern.

2. PULSAR MAGNETIC FIELDS AND ORIGINAL SPINS

Cyclotron features in the spectrum of an X-ray source can be used to determine the <u>total</u> surface magnetic field B of the neutron star. Thus, the feature in the hard X-ray spectrum of Her X-1 discovered by Trümper et al. (1978) implies $B \cong 4 \times 10^{12}$ G, if it is due to cyclotron scattering at $\lesssim$ 42 keV, or $B \cong 6 \times 10^{12}$ G, if due to cyclotron emission at $\cong$ 58 keV. A similar feature in the spectrum of 4U 0115+63 reported by Wheaton et al. (1978) implies $B \sim 2 \times 10^{12}$ G, if it is due to cyclotron scattering at $\sim$ 25 keV.

Both observational evidence and recent theoretical results suggest that most pulsing X-ray sources are disk-fed toward the end of their evolution (see Elsner et al. 1980). If a source is disk-fed, one can

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use its pulse frequency, frequency derivative, and total luminosity and the theory of disk accretion to estimate its dipole magnetic field (Ghosh and Lamb 1979). Excluding Vela X-1, acceptable fits to the secular spin-up rates of the currently measured sources are possible for dipole moments μ in the range $3 \times 10^{29} - 1.5 \times 10^{32}$ G cm^3, implying surface dipole fields B_d in the range $7 \times 10^{10} - 4 \times 10^{13}$ G (here and below we assume a surface radius of 16 km). Except for Her X-1, which is a fast rotator described by $\mu \cong 4.7 \times 10^{29}$ G cm^3 ($B_d \cong 1.1 \times 10^{11}$ G), there are two solutions for each source. However, in many stars the luminosity L varies, and this ambiguity can therefore be resolved by observing the variation of the pulse frequency with L.

Figure 1 shows how this method can be applied. Panels a and c show a sinusoidal luminosity variation of a factor of 2 and the corresponding variation in pulse frequency for a rigid star with $\mu = 1.0 \times 10^{30}$ G cm^3, while panels b and d show a series of large flares and the corresponding pulse frequency variation for a star with $\mu = 8.55 \times 10^{30}$ G cm^3. For simplicity, the luminosity variations shown are periodic. Actual luminosity variations are expected to be more complicated, but can be shown to lead to similar pulse frequency behavior. The luminosity pattern of panel b is consistent with the estimated luminosities of A0535+26 during its high and low states (Rappaport and Joss 1977, Cominsky et al. 1978) and leads to pulse frequency behavior in agreement with that observed during 1975-79, as shown in panel d, indicating that $\mu \cong 9 \times 10^{30}$ G cm^3 ($B_d \cong 2 \times 10^{12}$ G). Owing to observational and theoretical uncertainties, these values of μ and B_d must be considered preliminary estimates.

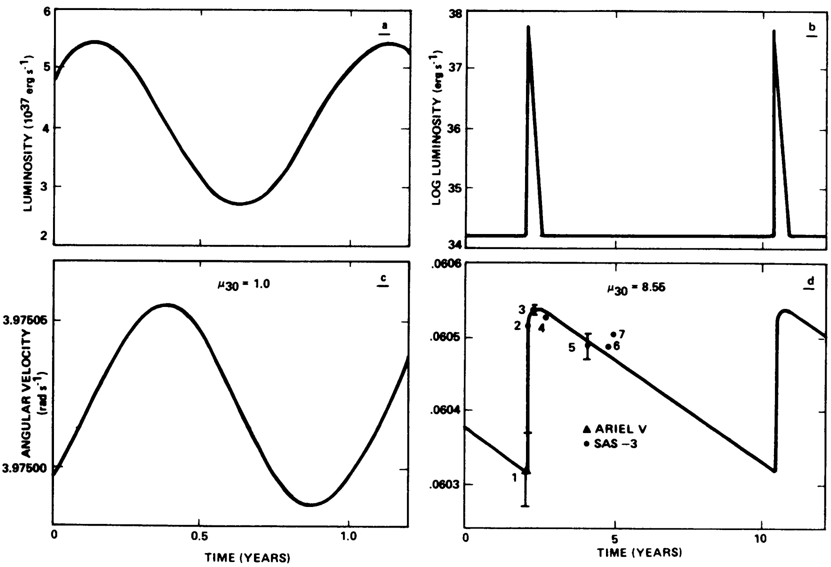

Fig. 1: Two examples of luminosity variations and the resulting pulse frequency behavior, illustrating the effects of different magnetic moments and luminosity patterns (from Elsner et al. 1980)

Most of the uncertainties permit larger but not smaller dipole fields (see Lamb 1977).

These results are inconsistent with the hypothesis that the dipole fields of all neutron stars decay in a few million years, since Her X-1 is estimated to be $\sim 5 \times 10^8$ years old, while the neutron stars in the massive X-ray binaries are several million years old (see van den Heuvel 1981). The persistence of strong magnetic fields in the pulsing X-ray sources suggests that the pulsars to which they give rise will have comparable fields for at least several million years, and hence that at least some pulsars do not turn off because their dipole fields decay, but for some other reason (compare Taylor and Manchester 1977).

Calculations of the evolution of massive X-ray binaries show that the rate of mass transfer increases steadily as the system evolves, leading eventually to formation of a common envelope, and ending with the collapse of the companion star's core (Savonije 1978, 1979, van den Heuvel 1980). The core collapse produces a runaway pulsar or a binary pulsar with a very eccentric orbit, such as PSR 1913+16. During the final evolution of the system, one expects the neutron star to accrete matter which is in Keplerian orbit at the magnetospheric boundary at a rate such that the accretion luminosity is approximately equal to the Eddington critical luminosity ($\sim 10^{38}$ erg s^{-1} for a star of $\sim 1\ M_\odot$). The spin period of the neutron star when the core collapses will then be comparable to the critical spin period,

$$P_c \cong 1.4\ \mu_{30}^{6/7}\ R_6^{-3/7}\ (M/M_\odot)^{-2/7}\ L_{38}^{-2/7}\ \mathrm{s}\ ,$$

at which the accretion torque vanishes (Ghosh and Lamb 1979). Here μ_{30} is the magnetic moment of the neutron star in units of 10^{30} G cm^3, R_6 is the stellar radius in units of 10^6 cm, M is the mass, and L_{38} is the final accretion luminosity in units of 10^{38} erg s^{-1}. If the magnetic moment of PSR 1913+16 has remained constant at $\sim 2 \times 10^{28}$ G cm^3, the value indicated by its current $\dot{P}$, this expression indicates that it was formed with a period $\sim$ 43 ms, close to its current period of 59 ms. In contrast, pulsars formed from X-ray sources with magnetic moments $\sim 10^{30}$ G cm^3, will have initial periods $\sim$ seconds.

These arguments suggest that many pulsars ejected from massive systems have periods $\sim$ seconds at the time of ejection. This has two interesting implications. First, the current periods of these pulsars may not be significantly different from their initial periods, with the result that the spin-down time scale τ_s is much longer than the time since formation. As noted by Taylor and Manchester (1977), this could explain the fact that the mean τ_s of the sample of pulsars they studied was much greater than the mean kinetic age. Second, the birth of pulsars with periods $\sim$ seconds implies that the death rate of pulsars with periods $\sim$ seconds must be even larger than would be the case if all pulsars were born with very short periods.

3. CONCLUSIONS

The evidence provided by the pulsing X-ray sources suggests that pulsars formed in massive binary systems are born with periods $\sim$ seconds and dipole magnetic fields $\sim 10^{11} - 10^{13}$ G. The observed persistence of strong fields for $\sim 3 \times 10^6 - 10^8$ years in the X-ray binaries suggests that the turnoff of at least some pulsars is not due to decay of their dipole magnetic fields.

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