X–ray Luminosity and Rotational Energy Loss of Isolated Neutron Stars

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Abstract. The relation between the X-ray luminosity L_X of isolated neutron stars and the rate of loss of their rotational energy $\dot{E}$ was first empirically determined by Seward & Wang (1988) using results from the Einstein satellite. We re-examine this relation on the basis of the larger sample observed with ROSAT, taking into account several uncertainties in the determination of L_X. Though similar to the previous one, the new *linear* relation is statistically unacceptable. The ROSAT data are better interpreted by introducing a different scaling between the younger objects in plerionic supernova remnants and the older pulsars.

1. Introduction

Besides the thermal radiation resulting from the cooling of their interior, isolated neutron stars emit X-rays as extended synchrotron nebulae or other non-thermal processes occurring in their magnetosphere and powered by the loss of rotational energy (see, e.g., Mereghetti et al. 1994; Ögelman 1995). An important parameter in studying these processes is the fraction of rotational energy loss converted into X-ray luminosity. Information about this critical factor can be inferred plotting the values of the X-ray luminosity L_X obtained from ROSAT observations against $\dot{E}$, as derived from the timing data $\dot{E} = 4\pi^2 I \dot{P} P^{-3}$.

The available sample of isolated neutron stars is now based on 18 sources. For each object, we have derived the value of L_X in the $[0.1 - 2.4]$ keV band, only considering the following contributions:

I) non-thermal, (pulsed) emission originated in the magnetosphere of young pulsars
II) extended synchrotron nebulae, produced by relativistic particles and magnetic field ejected by the pulsar
III) thermal emission coming from re-heating of (parts of) the photosphere by backward accelerated particles.

The contribution from internal cooling of the neutron stars has been excluded since it does not originate from $\dot{E}$.

2. Uncertainties on L_X

Contrary to Seward & Wang (1988), we want to derive a *weighted fit* of the L_X versus $\dot{E}$ data. Three different effects (whose relative importance differs for the various objects) contribute to the uncertainties in L_X:

- **uncertainties in the distances**
  For most of the pulsars, we have used the distances reported by Taylor, Manchester & Lyne (1993), which are usually based on the dispersion measures. In a few cases, we have adopted the distances derived from the ROSAT blackbody fits or from radio (or optical) parallax measurements. The distance uncertainties lead to typical errors of $\sim$0.2 in $\log(L_X)$.
- **statistical errors in the number of photons**
  The errors due to photon counting statistics dominate in the weak pulsars first detected with ROSAT, yielding uncertainties up to $\sim$0.5 in $\log(L_X)$. These are much smaller in the brighter objects.
- **uncertainties depending on the assumptions in the spectral and/or spatial modelling of the X-ray emission**
  These errors, the most difficult to quantify with a standard procedure, have been estimated on a case by case basis.

The sample can naturally be divided into 4 groups, based on their intrinsic and observational characteristics. After combining the three sources of error, it turns out that the resulting uncertainties in the L_X estimates are similar within each group:

a) Radio pulsars in X-ray emitting supernova remnants [$\Delta \sim \pm 0.2$]: *Crab, Vela, PSR 0540–69, PSR 1509–58, PSR 1951+32*
b) Old radio pulsars with re-heated polar caps [$\Delta \sim \pm 0.25$]: *PSR 1929+10, PSR 0950+08, PSR J0437–4715*
c) Middle-aged neutron stars dominated by thermal radiation [$\Delta \sim \pm 0.4$]: *PSR 1055–52, PSR 0656+14, Geminga*
d) Radio pulsars first detected in X-rays with ROSAT [$\Delta \sim \pm 0.6$]: *PSR 0114+58, PSR 0355+54, PSR 1706–*

44, PSR 0538+2817, PSR 1800–21, PSR 1823–13, PSR 2334+61

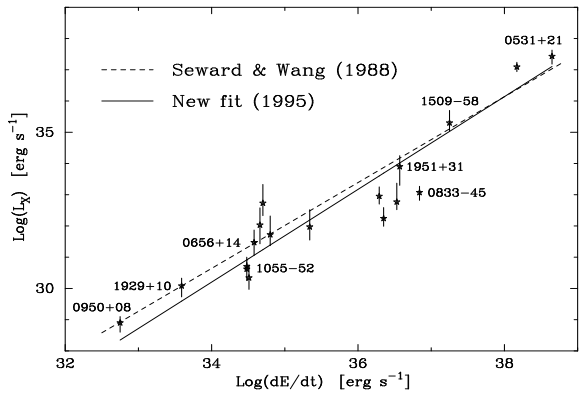

Fig. 1. The best linear fit to the L_X versus $\dot{E}$ data (solid line) is compared to that derived with the Einstein data (dashed line). The 8 sources used by Seward & Wang are labelled.

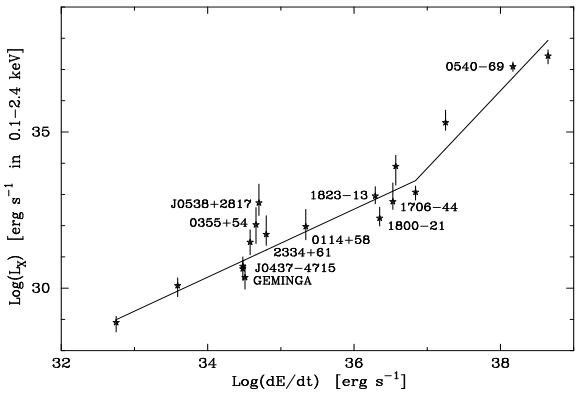

Fig. 2. The same data as Figure 1 fitted with a "broken line".

3. Results

A plot of L_X versus $\dot{E}$ for the 18 neutron stars of our sample is shown in Figure 1. A linear fit gives the relation:

$$\log(L_X) \;=\; 1.48\ \log(\dot{E}) \;-\; 20.3$$

but the resulting reduced χ^2_r of 7.65 (for 16 d.o.f.) is unacceptable. In order to produce a fit compatible with a single line ($\chi^2_r \sim 1$), we should increase the error bars for all pulsars in the sample up to an unrealistic value of $\Delta \sim \pm 0.80$.

Our fit is very similar to that determined by Seward & Wang (1988) based on 8 objects observed with the Einstein Observatory:

$$\log(L_X) \;=\; 1.39\ \log(\dot{E}) \;-\; 16.6$$

where L_X is the X-ray luminosity in the $[0.2 - 4.0]$ keV band. (Note, however, that also their linear fit was statistically unacceptable).

For middle-aged neutron stars Seward & Wang considered the total X-ray luminosity, which is now known to include a contribution from cooling that is unrelated to $\dot{E}$ (Ögelman 1995). This accounts for the slight increase of the slope between the previous and the current fit.

The new, larger sample suggests a steeper relation at higher values of $\dot{E}$; we have therefore fitted with a broken line. The best-fit relation (displayed in Figure 2) is:

$$\log(L_X) \;=\; \begin{cases} 1.09\ \log(\dot{E}) \;-\; 6.6 & \text{if } \log(\dot{E}) \leq 36.84 \\ 2.48\ \log(\dot{E}) \;-\; 58.0 & \text{if } \log(\dot{E}) > 36.84 \end{cases}$$

Though the reduced χ^2_r is still high (3.22 for 14 d.o.f.), we have verified with an F-test that the additional line (and the associated two new free parameters) significantly improves the fit (chance F-statistics probability of $\sim 2 \times 10^{-3}$).

4. Conclusions

The fact that the observed relation between $\log(L_X)$ and $\log(\dot{E})$ is not a simple linear law is not unexpected, considering the large span in $\dot{E}$ (and characteristic age) of these neutron stars and the different mechanisms contributing to their non-thermal X–ray emission. While the scarcity of data in the pre-ROSAT era justified a simple linear relation, the new observations must be interpreted in the context of specific models for the various physical processes, which obviously depend also on other parameters different from $\dot{E}$.

References

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