**BeppoSAX** observations of the young pulsar in the Kes 75 Supernova Remnant

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**ABSTRACT**

We present the results of **BeppoSAX** observations of the young X–ray pulsar PSR J1846–0258, recently discovered at the center of the composite supernova remnant Kes 75. The pulsar (plus nebula) spectrum can be fitted by an absorbed power law with photon index $\alpha_{ph} = 2.16 \pm 0.15$, $N_H = (4.7 \pm 0.8) \times 10^{22}$ cm$^{-2}$, and unabsorbed flux $\sim 3.9 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ (2–10 keV). By joining two observations taken at an interval of two weeks we have been able to obtain a precise measurement of the spin period ($P = 324.818968 \pm 0.000006$ ms). This value, when combined with previous measurements, cannot be fitted by a smooth frequency evolution with a canonical braking index $n = 3$. With the hypothesis of no glitches and/or significant timing noise, the braking index would be $n = 1.86 \pm 0.08$ and, assuming a short initial period, the pulsar age would be $\sim 1700$
years, closer to that of the supernova remnant than the simple estimate \( \tau = P/2\dot{P} = 723 \) years. Other likely possibilities involve the presence of glitches and lead to a wide range of acceptable ages. For example, we obtain \( n \) in the range 1.8–2.5, if a glitch occurred near MJD 51500 while for a glitch between October 1993 and March 1999 we can only get a lower limit of \( n > 1.89 \).

Subject headings: Pulsars: individual (PSR J1846–0258) – Stars: neutron – Supernovae: individual (G29.7–0.3)

1. Introduction

The X–ray pulsar PSR J1846–0258 (\( P = 325 \) ms) was discovered by Gotthelf et al. (2000) at the center of the composite supernova remnant Kes 75 (G29.7–0.3). Up to now, no radio detection of PSR J1846–0258 has been reported, with an upper limit of \( \sim 0.1 \) mJy at 1.5 GHz (Kaspi et al. 1996). All the information on the pulsar timing parameters has been determined through observations in the X–ray band. Gotthelf et al. (2000) obtained a period derivative of \( \dot{P} = 7.1 \times 10^{-12} \) s s\(^{-1} \), by comparing five period measurements obtained with the RossiXTE and ASCA satellites in the years from 1993 to 2000. Assuming the canonical relation for the spin-down by magnetic dipole radiation, these values lead to an estimate for the magnetic field of \( B \sim 5 \times 10^{13} \) G, above the quantum critical field and in the range of the highest values observed in radio pulsars. Even more remarkably, the characteristic age of PSR J1846–0258, \( \tau = P/2\dot{P} = 723 \) years, is the smallest one of any known pulsar.

The association of PSR J1846–0258 with the supernova remnant Kes 75 can be regarded as almost certain: the pulsar is located at the geometrical center of the 3.5‘ diameter shell (Collins, Gotthelf & Helfand 2002) and is powering a bright radio/X–ray nebula that gives the composite morphology to this supernova remnant. The estimate of the age of Kes 75 is subject to a large uncertainty. Assuming that the shell is still in the freely expanding phase with velocity \( v \), the age is \( 1800d_{19}(v/5000\) km s\(^{-1})^{-1} \) years, where \( d_{19} \) is the distance normalized to the value of 19 kpc, estimated for Kes 75 with 21 cm observations (Becker & Helfand 1984). Alternatively, if the remnant is already in the Sedov phase, the age can be estimated by the relation between the radius and the shock temperature inferred from the X–ray spectra. In this way Blanton & Helfand (1996) derived an age of 7000 \( d_{19} \) years, based on the temperature of 0.5 keV measured with ASCA. It thus appears that the pulsar characteristic age is smaller than the age of Kes 75, although the large uncertainties involved do not allow agreement between the two values to be precluded.
2. Observations and Data Analysis

The location of PSR J1846–0258 was observed twice with the BeppoSAX satellite in March 2001 (see Table 1). The instrument relevant for the observations reported here is the Medium-Energy Concentrator Spectrometer (MECS), that operates in the 1.8–10 keV energy range, providing a good spatial (∼1′ full width at half maximum (FWHM)) and energy resolution (∼8.5% FWHM at 6 keV) over a circular field of view with a diameter of 56′ (Boella et al. 1997).

The main target of the first observation (A) was the pulsar AX J1844–0258, therefore PSR J1846–0258 was detected at an off-axis angle of ∼23′ (results on AX J1844–0258 will be reported elsewhere). The second observation (B) was pointed on the Kes 75 supernova remnant. Both observations lasted about 2.5 days, but Earth occultations and passage of the satellite in regions of high particle background resulted in net exposure times of 83.7 ks and 105.3 ks for the MECS instrument.

2.1. Timing analysis

For the timing analysis we used only counts with energy greater than 3 keV in order to reduce the contribution of the soft emission from the supernova remnant. For observation B we used a circular extraction region with radius 2′ (resulting in 15904 counts), while for observation A we used an elliptical region matched to the shape of the off-axis MECS point spread function (3751 counts). The times of arrival were converted to the Solar System barycenter using the source position R.A. = 18h 46m 24.5s, Dec. = −02° 58′ 28″ (J2000).

We first analyzed the two observations separately, using a folding program to search over a grid of period (P) and period derivative (Ṗ) values and adopting the method described in Leahy (1987) to determine the best period and its uncertainty. Since the individual observations are relatively short compared to the pulsar spin-down timescale, the period values giving the highest signal do not depend significantly on Ṗ. We therefore fixed Ṗ to the value 7.097 × 10^{-12} s s^{-1} (Gotthelf et al. 2000) obtaining the period values reported in Table 1. The light curve obtained from observation B is shown, for different energy ranges, in Fig. 1. The difference between the periods measured in the two observations corresponds to Ṙ = (7.127 ± 0.096) × 10^{-12} s s^{-1} which is, within the errors, compatible with the value found from the ASCA and RossiXTE data spanning the years 1993−2000 (Gotthelf et al. 2000).

The accuracy of the BeppoSAX satellite clock is good enough to combine the two observations (taken about 15 days apart) into a single data set, thus allowing us to derive
a smaller error on $P$ and to directly measure $\dot{P}$. This was again done by folding the data on a grid of $P$ and $\dot{P}$ trial values, leading to $P = 324.818968 \pm 0.000006$ ms and $\dot{P} = (7.095 \pm 0.086) \times 10^{-12}$ s s$^{-1}$, where the values refer to the epoch MJD=51991.08778. These results are consistent with an extrapolation of the timing solution derived by Gotthelf et al. (2000).

2.2. Spectral analysis

For the spectral analysis we used only observation B that provided data of better quality since PSR J1846–0258 was detected on-axis, where the MECS instrument has the greatest sensitivity and the best spectral and spatial performances. Moreover, we used also data from the LECS instrument (Parmar et al. 1997) that covers the soft energy range down to 0.1 keV.

For the source spectrum extraction we used first a circle of radius 4$'$ for the MECS and 8$'$ for the LECS in order to maximize the contribution from both the supernova remnant and the pulsar nebula emission. The background spectrum was estimated from a circular corona between 4.7$'$ and 9.5$'$ for the MECS and between 8$'$ and 10.6$'$ for the LECS. The source spectra were rebinned in order to have at least 30 counts per channel.

We verified that a fit with a power-law only fails to describe the data ($\chi^2$/d.o.f. = 463/404), giving strong residuals corresponding to the presence of the emission lines of Si XIII (1.84 keV) and S XV (2.45 keV). We therefore fitted the spectra using a combination of a power law and an optically thin thermal plasma (mekal in the XSPEC software package v.11), plus an interstellar absorption of Morrison and McCammon (1983). This combination of models is known to be appropriate for Kes 75, because it also takes into account the presence of a thermal shell (Blanton & Helfand 1996). This model produced a very good fit ($\chi^2$/d.o.f. = 398/402) with the following parameters: interstellar absorption $N_H = 4.7(3.9 - 5.5) \times 10^{22}$ cm$^{-2}$, photon index $\alpha_{ph} = 2.19(2.07 - 2.30)$, plasma temperature $kT = 0.40(0.35 - 0.53)$ keV. This best-fit is shown in Fig. 2. The thermal and non-thermal fluxes in the 0.1–2 keV range are respectively $10.1(3.0 - 24.4) \times 10^{-10}$ and $9.9(7.9 - 12.0) \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, while the corresponding values in the 2–10 keV band are $5.4(1.6 - 13.0) \times 10^{-12}$ and $3.4(2.7 - 4.1) \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. The contribution of the thermal component to the flux density drops below 10% of the total above 3 keV. To further constrain the spectrum of the nebula, we have repeated the analysis using the data collected from a smaller circle (2$'$ radius), and fixing the temperature of the thermal component and the interstellar absorption to the values obtained previously. This resulted in a best-fit with $\alpha_{ph} = 2.16(2.10 - 2.21)$ ($\chi^2$/d.o.f. = 348/317). The non-thermal unabsorbed flux in the 2–10 keV band is $3.9(3.5 - 4.2) \times 10^{-11}$ erg cm$^{-2}$
These results are consistent with (and have smaller uncertainties than) those obtained by Blanton & Helfand (1996) with *ASCA* that, similarly to our instrument, did not have enough spatial resolution to disentangle the contribution from the shell and the central pulsar/ nebula.

We also examined the pulsar spectrum in two different phase intervals corresponding to the high and low parts of the pulse profile, finding marginal evidence for a hardening in correspondence of pulse maximum. This indicates that the surrounding diffuse X–ray nebula, giving a higher relative contribution during the phase of low pulsed emission, has a spectrum softer than that of the pulsar. In fact, the preliminary *Chandra* results reported by Collins et al. (2002), yield a power law photon index of \( \sim 1.5 \) for the pulsar and \( \sim 1.9 \) for the nebula.

### 3. Discussion

The period measurement derived with *BeppoSAX*, together with past measurements (as from Table 1 in Gotthelf et al. 2000), allows an analysis of the rotation history of PSR J1846–0258 in the past decade. All together, there are now 6 different measurements, of which ours is that with the smallest uncertainty (just 12% of the average of all the others). In the case of a smooth evolution represented with a quadratic function, of the form

\[
\nu(t) = \nu_0 + \dot{\nu}_0(t - t_0) + \frac{1}{2} \ddot{\nu}_0(t - t_0)^2,
\]

a reasonable representation of the data can be achieved with the best fit parameters reported in the first column of Table 2 (\( \chi^2 = 3.52 \), for 3 d.o.f.; residuals are plotted in Fig. 3.b). The best fit second derivative of the frequency \( \ddot{\nu}_0 \) is significantly different from 0. In fact a linear fit \( (\ddot{\nu}_0 = 0) \) can be safely ruled out, as shown by the extremely high \( \chi^2 \) value (\( \sim 534 \), for 4 d.o.f.). We also note that the residuals of a linear fit (Fig. 3.a) are too large to be accounted for by timing noise, even assuming for PSR J1846–0258 a particularly high activity parameter (see, e.g., Arzoumanian et al. 1994).

Under the hypothesis that no glitch has occurred over the time spanned by the period measurements, the available data can be used to determine the braking index \( n \), defined by the law \( \dot{\nu} \propto -\nu^n \) and evaluated, in terms of the frequency and its first two derivatives, as

\[
n = \frac{\nu \ddot{\nu}}{\dot{\nu}^2}.
\]

The values of the quadratic fit correspond to a braking index \( n = 1.86 \pm 0.08 \), significantly lower than the canonical value \( (n = 3) \) for magnetic dipole losses. For a braking law \( \dot{\nu} \propto -\nu^n \), the pulsar age is:
\[ \tau = \frac{P}{(n-1)\dot{P}} \left[ 1 - \left( \frac{P_0}{P} \right)^{n-1} \right]. \]

Assuming an originally fast spinning pulsar ($P_0 \ll P$), we derive for PSR J1846–0258 an age $\tau = 1675 \pm 157$ yr. The quoted accuracy on $\tau$ relies on the assumption that irregularities in the spin evolution are negligible in the range of epochs spanned by the observations. In particular, if found that one or more glitches have occurred in between period measurements, the above estimates should be revised. Although population studies indicate small initial periods for radio pulsars (Bhattacharya et al. 1992, Lorimer et al. 1993) and a value of $P_0 \sim 17 - 19$ ms is generally accepted for the Crab pulsar, there is now considerable evidence that fairly long initial spin periods may be common (see, e.g., Torii et al. 1999, Kaspi et al. 2001, Murray et al. 2002). We therefore show in Fig. 4 (solid line), how the age derived from equation (1) depends on the assumed value of $P_0$.

The data can also be interpreted by considering the possibility that glitches occurred between the observations. For instance, let us first consider the case of a glitch between the first (October 1993) and the second (March 1999) measurements by comparing the October 1993 value with the extrapolation of a fit to the subsequent measurements. A quadratic fit to the last five points gives a poorly constrained $\ddot{\nu}$ (corresponding to $n = 0.84 \pm 0.68$; see column (2) in Table 2). The estimated magnitude and even the sign of the glitch actually depend on the value of the braking index. The best fit ($n = 0.84$) corresponds to a negative jump in frequency, a behavior opposite to what seen in all glitching radio pulsars (Lyne et al. 2000). A conventional sign is obtained only for $n > 1.89$, which being at only $\sim 1.5\sigma$ from the best fit, has a non negligible probability.

Another possibility is the occurrence of a glitch at a later time. In fact the residuals in Fig. 3.b show a pattern suggesting a glitch in an epoch between the third and fourth data point. We have then chosen 51500.0 MJD as a possible epoch of this glitch: any different choice of the epoch, within the time interval between the third and fourth data point, will have the only effect of slightly changing the best parameters for the glitch, therefore not changing any of the conclusions that we shall draw below.

For different values of the braking index, we have fitted separately the former and latter set of three data points. We find that for values of $n$ larger than about 2.5 we would again come out with an unlikely “anti-glitch”. On the other hand, for $n$ smaller than about 1.8 the (negative) $\dot{\nu}$ should increase, and also this behavior is in contrast with what seen in radio pulsars (Lyne et al. 2000). In the allowed range for $n$ (1.8, 2.5), the $\chi^2$ value is monotonically decreasing for increasing $n$, but the trend is so shallow that by itself it cannot be taken as a valid argument for preferring higher values of $n$. The parameters for the two limit cases are
shown in columns (3) and (4) of Table 2, and the corresponding pulsar ages by the dashed lines of Fig. 4.

If a glitch at about MJD 51500 actually occurred, how does it compare with known glitches in other pulsars? Fig. 5 shows the positions, in the parameter plane \((\Delta \nu/\nu)-(\Delta \dot{\nu}/\dot{\nu})\) of all glitches known in radio pulsars for which both \(\Delta \nu\) and \(\Delta \dot{\nu}\) have been measured (as from Lyne et al. 2000). Superposed is the locus of the points representing the MJD 51500 glitch, for different values of \(n\). It is apparent that the required glitch has rather normal parameters, with both \((\Delta \nu/\nu)\) and \((\Delta \dot{\nu}/\dot{\nu})\) somehow smaller than the average.

4. Conclusions

We have presented a new accurate measurement of the spin frequency of the young pulsar PSR J1846–0258 associated to the Kes 75 supernova remnant. Combined with previous data, and making some hypothesis on the glitch history of PSR J1846–0258 our new frequency measurement can be interpreted in different ways.

A simple possibility, assuming no glitches in the years 1993–2001, is in terms of a timing solution with \(\ddot{\nu} = (2.77 \pm 0.12) \times 10^{-21}\) Hz s\(^{-2}\). This results in a braking index \(n = 1.86 \pm 0.08\) and an estimate for the age of PSR J1846–0258 more in accord with that of the associated supernova remnant (unless the pulsar initial period was close to the current one). Other likely possibilities involve a single glitch with reasonable parameters and lead to a wide range of acceptable ages. If the glitch occurred near MJD 51500 the resulting braking index \(n\) is in the range 1.8–2.5, while for a glitch between October 1993 and March 1999 we can only get a lower limit of \(n > 1.89\).

Braking indices have so far been measured only for five pulsars. Except for PSR J1119–67 which has \(n = 2.91 \pm 0.05\) (Camilo et al. 2000), all of them have \(n\) significantly smaller than 3, similar to the values suggested by our analysis for PSR J1846–0258. Such values are 2.51 \(\pm 0.01\) (Crab pulsar; Lyne, Pritchard & Graham-Smith 1993), 2.837 \(\pm 0.001\) (PSR B1509–58; Kaspi et al. 1994), 1.4 \(\pm 0.2\) (Vela pulsar; Lyne et al. 1996), and 1.81 \(\pm 0.07\) (PSR B0540–69; Zhang et al. 2001).

The pulsar with the highest glitch rate (about one per year) in the sample studied by Lyne et al. (2000), is PSR B1737–30, which is also the one with the highest magnetic field \((1.7 \times 10^{13}\) G\). We cannot exclude that PSR J1846–0258 had more than one glitch in the eight years spanned by the observations, but in this case no information on \(n\) can be derived from our data. Interestingly, the glitch parameters we inferred for PSR J1846–0258 in Fig. 5 are similar to those observed in PSR B1737–30. A finer monitoring in the future will establish
whether PSR J1846–0258 is indeed similar to PSR B1737–30.

As already mentioned by Gotthelf et al. (2000), the $P$ and $\dot{P}$ values of PSR J1846–0258 are very similar to those of the radio pulsar PSR J1119–6127 ($P = 407.6$ ms, $\dot{P} = 4 \times 10^{-12}$ s s$^{-1}$, Camilo et al. 2000). A remarkable difference between these two young and energetic pulsars ($\dot{E}_{\text{rot}} \gtrsim 2 \times 10^{36}$ erg s$^{-1}$) is the lack of a bright pulsar wind nebula around PSR J1119–6127 (Crawford et al. 2001). These authors suggested that high magnetic field pulsars produce radio nebulae that fade rapidly, an interpretation apparently contradicted by the brightness of the Kes 75 core. If the value $n = 1.86$ is confirmed for PSR J1846–0258, the difference in the brightness of the wind nebulae of these two pulsars might be related to their different braking index values ($n = 2.91 \pm 0.05$ for PSR J1119–6127; Camilo et al. (2000)). While spin-down by magnetic dipole radiation yields $n = 3$, a value $n = 2$ is expected if the pulsar braking is driven by the presence of a strong relativistic wind, which could also have an effect on the emission from a surrounding nebula.

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Table 1. Log of *BeppoSAX* observations

| Observation | Start date | MJD<sup>a</sup>  | Exposure time | Period<sup>b</sup> |
|-------------|------------|------------------|---------------|-------------------|
| A           | March 14, 2001 | 51983.27098      | 83716 s       | 324.81411(12) ms |
| B           | March 29, 2001 | 51998.86160      | 105327 s      | 324.82371(5) ms  |

<sup>a</sup> Modified Julian Date of the middle of the observation

<sup>b</sup> values referred to the Epoch of Column (3) and for fixed $\dot{P} = 7.097 \times 10^{-12} \text{ s}^{-1}$ (as from Gotthelf et al. 2000)
Table 2. Derived timing parameters for PSR J1846–0258 (1σ uncertainties)

|                  | all the points | last five points | all the points$^a$ | all the points$^a$ |
|------------------|----------------|------------------|-------------------|-------------------|
|                  | (1)            | (2)              | (3)               | (4)               |
| $t_o$ (MJD)      | 50000.0        | 50000.0          | 51500.0           | 51500.0           |
| $\nu_0$ (Hz)     | 3.090255(1)    | 3.09024(1)       | 3.0814965(7)      | 3.0814947(7)      |
|                  |                |                  | 3.0814965(5)      | 3.0814963(5)      |
| $\dot{\nu}_0$ ($10^{-11}$ Hz s$^{-1}$) | $-6.7768(14)$  | $-6.754(15)$     | $-6.7319(11)$     | $-6.7422(11)$     |
|                  |                |                  | $-6.7448(12)$     | $-6.7422(12)$     |
| $\ddot{\nu}_0$ ($10^{-21}$ Hz s$^{-2}$) | $2.77 \pm 0.12$ | $1.2 \pm 1.0$   | $[3.647]^b$       | $[2.685]$         |
|                  |                |                  | $[3.661]$         | $[2.685]$         |
|                  |                |                  |                   |                   |
| $\chi^2$/d.o.f. | 3.52/3         | 1.18/2           | 0.029/1           | 0.086/1           |
|                  |                |                  | 0.240/1           | 0.508/1           |
| Total:           |                |                  | 0.269/2           | 0.594/2           |
| $n$              | 1.86 $\pm$ 0.08 | 0.84 $\pm$ 0.68 | 2.48$^c$          | 1.82$^c$          |
| $\tau$ (yr)     | 1675 $\pm$ 157 |                  | [980.1]           | [1766.2]          |
|                  |                |                  | [978.2]           | [1766.2]          |

$^a$ The upper and lower values in each line refer respectively to the fit to data points before and after MJD 51500.

$^b$ All the values within square brackets strongly depend on the assumed $n$ value.

$^c$ Assumed value
Fig. 1.— Folded light curve of PSR J1846–0258 in three energy ranges, obtained with the MECS instrument in the observation of March 29th, 2001.

Fig. 2.— Best fit spectrum of PSR J1846–0258 (upper panel) and residuals (lower panel). The points correspond to the LECS (0.5-9 keV) and MECS (1.8-10 keV) data. The lines in the upper panel are the best fit model folded through the instrumental response.

Fig. 3.— Residuals of the fits to the spin frequency as a function of time for the cases (a) of a linear and (b) of a quadratic relation. Note the different scales of the vertical axis. The vertical line in plot (b) indicates the possible location of a glitch, that may account for the pattern of the residuals (see text).

Fig. 4.— Age of PSR J1846–0258 as a function of its initial spin period. The solid line refers to $n = 1.86$, the dotted line to $n = 3$, and the dashed lines indicate the range allowed by values of $n$ in the interval $1.82 - 2.48$.

Fig. 5.— Parameters of the glitch fitted to the PSR J1846–0258 data compared with the values of $(\Delta \nu/\nu)$ and $(\Delta \dot{\nu}/\dot{\nu})$ of glitching pulsars (Lyne et al. 2000). The line indicates the values obtained for different assumptions on the braking index value; the empty dots represent all braking indices from 1.85 to 2.45, separated by 0.05. The circled dots represent the glitches of the highest field radio pulsar in the sample (PSR 1737–30, with $B = 1.7 \times 10^{13}$ G): they have parameters similar to those expected for the possible MJD 51500 glitch in PSR J1846–0258.
PSR J1846-0258

$P=0.324818968$ s, $dP/dt=7.095 \times 10^{-12}$ s s$^{-1}$

3–10 keV

3–6 keV

6–10 keV
