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A *BeppoSAX* OBSERVATION OF KS 1731−260 IN ITS QUIESCENT STATE: CONSTRAINTS ON THE MAGNETIC FIELD OF THE NEUTRON STAR

L. Burderi,[1] T. Di Salvo,[2,3] L. Stella,[1] F. Fiore,[1] N. R. Robba,[3] M. van der Klis,[2] R. Iaria,[3] M. Mendez,[4] M. T. Menna,[1] S. Campana,[5] G. Gennaro,[6] S. Rebecchi,[7] and M. Burgay[8]
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ABSTRACT

We report here the results of a 90 ks *BeppoSAX* observation of the low-mass X-ray binary and atoll source KS 1731−260 during a quiescent phase. From this observation we derive a source X-ray luminosity of $\sim 10^{33}$ ergs s^{-1} (for a source distance of 7 kpc). If the neutron star is spinning at a period of a few milliseconds, as inferred from the nearly coherent oscillations observed during type I X-ray bursts, the quiescent X-ray luminosity constrains the neutron star magnetic field strength. We consider all the mechanisms that have been proposed to explain the quiescent X-ray emission of neutron star X-ray transients and compare the corresponding expectations with the measured upper limit on the X-ray luminosity. We find that, in any case, the neutron star magnetic field is most probably less than $\sim 10^9$ G. We have also observed KS 1731−260, still in its quiescent state, at 1.4 GHz with the Parkes radio telescope to search for radio pulses. We found that no radio signals with millisecond periods are present with an upper limit on the flux of 0.60 mJy using a 4 minute integration time (optimal for a close system with an orbital period smaller than a few hours) and of 0.21 mJy using a 35 minute integration time (optimal for a wide-orbit system).

Subject headings: accretion, accretion disks — stars: individual (KS 1731−260) — stars: neutron — X-rays: general — X-rays: stars

1. INTRODUCTION

The Galactic X-ray source KS 1731−260 was discovered in 1989 August with the Coded Mask Imaging Spectrometer (COMIS, or TTM following the Russian abbreviation) on the *Mir-Kvant* observatory (Sunyaev 1989; Sunyaev et al. 1990). During the ∼15 day long *Mir-Kvant* observation, the source intensity varied from 50 to 100 mcrab in the 2–27 keV band. The presence of three type I bursts indicated that the compact object is an accreting neutron star (NS) and that the source distance is about 7 kpc (Muno et al. 2000). The factor of 10 intensity variations displayed by the source suggested that KS 1731−260 is a transient source (e.g., Sunyaev et al. 1990). There have been numerous detections of the source at a level of 50–100 mcrab since its discovery in 1989, and the monitoring by the *Rossi X-Ray Timing Explorer* (*RXTE*) All Sky Monitor (ASM) showed that the source was continuously active until 2001 February. Therefore, the source appeared to belong to a group of NS soft X-ray transients (SXTs) that display active states extending for a number of years (as opposed to outbursts decaying on timescales of a few months; see Campana et al. 1998a for a review).

The source spectrum resembles that of other SXTs in outburst; the TTM spectrum taken on 1989 August 16–31 could be fitted to a thermal bremsstrahlung with $kT \sim 5.7$ keV, while the spectrum obtained by SIGMA on 1991 March 14 (when the source was somewhat fainter: 9×10^{36} ergs s^{-1} as opposed to 1.5×10^{37} ergs s^{-1}) was well modeled by a power law with a photon index of ∼2.9 extending up to 150 keV at least. The source detection during the *ROSAT* all-sky survey yielded a fairly accurate measurement of column density, $N_{\rm H} = (1.00 \pm 0.19) \times 10^{22}$ cm^{-2} (Barret, Motch, & Predehl 1998).

Based on an *RXTE* Proportional Counter Array (PCA) observation in 1996 July, Smith, Morgan, & Bradt (1997) discovered a nearly coherent signal at 523.92 ± 0.05 Hz (corresponding to a period of 1.91 ms) during a 2 s interval close to the beginning of the decay of a type I X-ray burst. This signal, as well as similar signals observed during type I X-ray bursts from about 10 low-mass X-ray binaries, likely corresponds to the NS rotation frequency (or twice its value; for a review, see Strohmayer, Swank, & Zhang 1999). An *RXTE* observation on 1996 August 1 (Wijnands & van der Klis 1997) revealed two simultaneous quasi-periodic oscillations (QPOs) in the persistent emission of KS 1731−260 at 898 and 1159 Hz, the frequency separation of which (260.3 ± 9.6 Hz) is compatible with half the frequency of the nearly coherent signal observed in the type I bursts. In the beat-frequency model for the kilohertz QPOs, this corresponds to a NS spinning at a period of 3.8 ms, which might imply that only the first harmonic is detected during type I bursts (although this case seems to be unlikely; see Muno et al. 2000).

RXTE/ASM data showed that the source entered a quiescent state in 2001 February (upper limit of 2 counts s^{-1}

[1] Osservatorio Astronomico di Roma, Sede di Monteporzio Catone, Via Frascati 33, Rome I-00040, Italy; burderi@coma.mporzio.astro.it.
[2] Astronomical Institute "Anton Pannekoek" and Center for High-Energy Astrophysics, University of Amsterdam, Kruislaan 403, Amsterdam NL-1098 SJ, Netherlands; disalvo@astro.uva.nl.
[3] Dipartimento di Scienze Fisiche ed Astronomiche, Università di Palermo, Via Archirafi 36, Palermo I-90123, Italy.
[4] SRON National Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, Netherlands.
[5] Osservatorio Astronomico di Brera, Via Bianchi 46, Merate I-23807, Italy.
[6] Telespazio, Direzione Generale, Via Tiburtina 965, Rome I-00156, Italy.
[7] Consorzio Interuniversitario per la Fisica Spaziale/Agenzia Spaziale Italiana, Viale Regina Margherita 202, Rome I-00198, Italy.
[8] Dipartimento di Astronomia, Università di Bologna, via Ranzani 1, Bologna I-40127, Italy.

corresponding to a luminosity of less than 3×10^{36} ergs s^{-1}). A few months after (on 2001 March 27), KS 1731−260 was observed by *Chandra*; it was still in quiescence with a 0.5–10 keV bolometric luminosity of $\sim 10^{33}$ ergs s^{-1} (assuming a distance of 7 kpc) and an X-ray spectrum that is well described by a blackbody at a temperature of $\sim$0.3 keV (Wijnands et al. 2001b). The same data were also analyzed by Rutledge et al. (2001); they fitted the spectrum using a hydrogen atmosphere model, obtaining an effective temperature of 0.12 keV, an emission area radius of $\sim$10 km, and a bolometric luminosity of $\sim 2.7 \times 10^{33}$ ergs s^{-1} (assuming a distance of 8 kpc). We present here the results of a 200 ks *BeppoSAX* observation of KS 1731−260 taken in 2001 March, just after the beginning of this quiescent state, in which the source was detected at a quiescence luminosity level of $(7 \pm 2) \times 10^{32}$ ergs s^{-1}.

2. OBSERVATIONS AND DATA ANALYSIS

KS 1731−260 was observed with the *BeppoSAX* Narrow Field Instruments (NFIs) from 2001 March 2, 23:28 UT to March 5, 19:07 UT for 200 ks. The effective exposure time was $\sim$91 ks. The NFIs consist of four co-aligned instruments, namely, the Low Energy Concentrator Spectrometer (LECS), a thin-window position-sensitive proportional counter with extended low-energy response in the band 0.1–10 keV (Parmar et al. 1997; due to UV contamination problems, the LECS was operated only at satellite night time, resulting in a reduced exposure time with respect to the other instruments); two (originally three) Medium Energy Concentrator Spectrometers (MECSs), operating in the 1.3–10 keV band (Boella et al. 1997); a High Pressure Gas Scintillation Proportional Counter (HPGSPC), sensitive in the energy range 7–60 keV (Manzo et al. 1997); and a Phoswich Detection System (PDS), sensitive in the energy range 13–200 keV (Frontera et al. 1997), consisting of four independent Na I (Tl)/Cs I (Na) phoswich scintillation detectors.

Images from the two MECSs were summed, and the events with pulse-height analyzer energies between 1.3 and 10 keV were considered. We searched for sources in the MECS field of view (FOV) around the nominal position of KS 1731−260 (Barret et al. 1998). We found a source centered at the position R.A. $= 17^h34^m09^s.4$, decl. $= -26°06'22''$ (J2000.0) and extracted all the photons from a 1'.8 radius circle (corresponding to 64% of the point-spread function [PSF]).[9] The size of the extraction region was determined to optimize the signal-to-noise ratio. The accuracy and stability of the pointing during the *BeppoSAX* observation of KS 1731−260 has been checked and the satellite attitude has been verified within each orbit by telemetry reconstruction. In particular, we have verified that the positions of the stars in the onboard star tracker's FOV remained constant during all the observation. In principle, the error on the *BeppoSAX*/MECS position is $\sim$0'.55 (1 σ confidence level); however, given the possibility of confusion with other unresolved sources (see below), we consider the radius of the extraction region, 1'.8, as a conservative estimation of the error on the source position.

The recently reported source position based on a *Chandra* observation performed on 2001 March 27 and corrected for an offset with respect to the Two Micron All Sky Survey (2MASS; Wijnands et al. 2001a)[10] is R.A. $= 17^h34^m13^s.47$, decl. $= -26°05'18''.8$ (J2000.0). Therefore, our derived position differs by 1'.40 from the *Chandra* position, which is still within the 1'.8 radius circle. Because of the position of the source close to the Galactic center, the possibility of contamination from diffuse emission and other sources, which might fall within the 1'.8 radius circle, must be considered. Indeed, in the *Chandra* observation of KS 1731−260, another X-ray source (probably an X-ray active star) was detected at 0'.5 from KS 1731−260 (Wijnands et al. 2001a, 2001b). The MECS FOV, with the source we detected, is shown in Figure 1. The position of the *Chandra* sources are also indicated in the figure. Therefore, the luminosity we derive for KS 1731−260 should be considered as an upper limit.

With this caveat in mind, we derived the luminosity of the source in the following way. Since standard background-subtraction methods based on blank-sky observations were not applicable, we extracted background counts from nearby source-free regions. The background was taken from a region within the central 8' of the MECS FOV. We checked that the number of source photons estimated did not vary within 20% using background boxes of different sizes and locations. Of the 280 events detected within the 1'.8 radius circle centered on the source position, 210 events ($\sim$75% of the total) are expected to be background events. This corresponds to a 3.7 σ detection. From these data, we extracted a light curve; no short-term variability was significantly detected during the *BeppoSAX* observation. The count rate corrected for the PSF is $(1.20 \pm 0.33) \times 10^{-3}$ counts s^{-1}. Because the statistics in the MECS spectrum were not enough to constrain the spectral model, we considered different spectral models, namely, a blackbody (with temperatures ranging between 0.2 and 1 keV) and a power law (with photon indices ranging between 1.5 and 2.9). In all cases, the column density N_H was fixed at 1.0×10^{22} cm^{-2}, consistent with the value obtained from the *ROSAT* and *Chandra* observations (Barret et al. 1998; Wijnands et al. 2001b). Within 10%, all the models yield a flux of $\sim 1 \times 10^{-13}$ ergs cm^{-2} s^{-1} in the 1.3–10 keV band. For a blackbody of temperature 0.3 keV (in agreement with the blackbody fitted to the *Chandra* data of KS 1731−260; Wijnands et al. 2001b), adopting a distance of 7 kpc (Muno et al. 2000), the corresponding bolometric luminosity is $(7 \pm 2) \times 10^{32}$ ergs s^{-1}. This value is compatible with the 0.5–10 keV bolometric luminosity of $\sim 10^{33}$ ergs s^{-1} deduced from the *Chandra* observation (Wijnands et al. 2001b). As a cross-check, we also extracted the data in the MECS FOV using a circular region of 4' radius (within which $\sim$90% of the source counts are expected) centered on the nominal position of KS 1731−260. In this case, the background was measured from a region of the MECS image 20' away from the FOV center and divided by a factor of 0.85 to take into account the reduction of the effective area with the increase of the distance from the FOV center. In this case, the background contributed $\sim$80% of the total source plus background spectrum. The estimated bolometric (unabsorbed) source luminosity was $\sim 1.4 \times 10^{33}$ ergs s^{-1} using a black-

[9] Available for download from ftp://ftp.asdc.asi.it/pub/sax/doc/software_docs/saxabc_v1.2.ps.gz.

[10] Available at http://atel.caltech.edu.

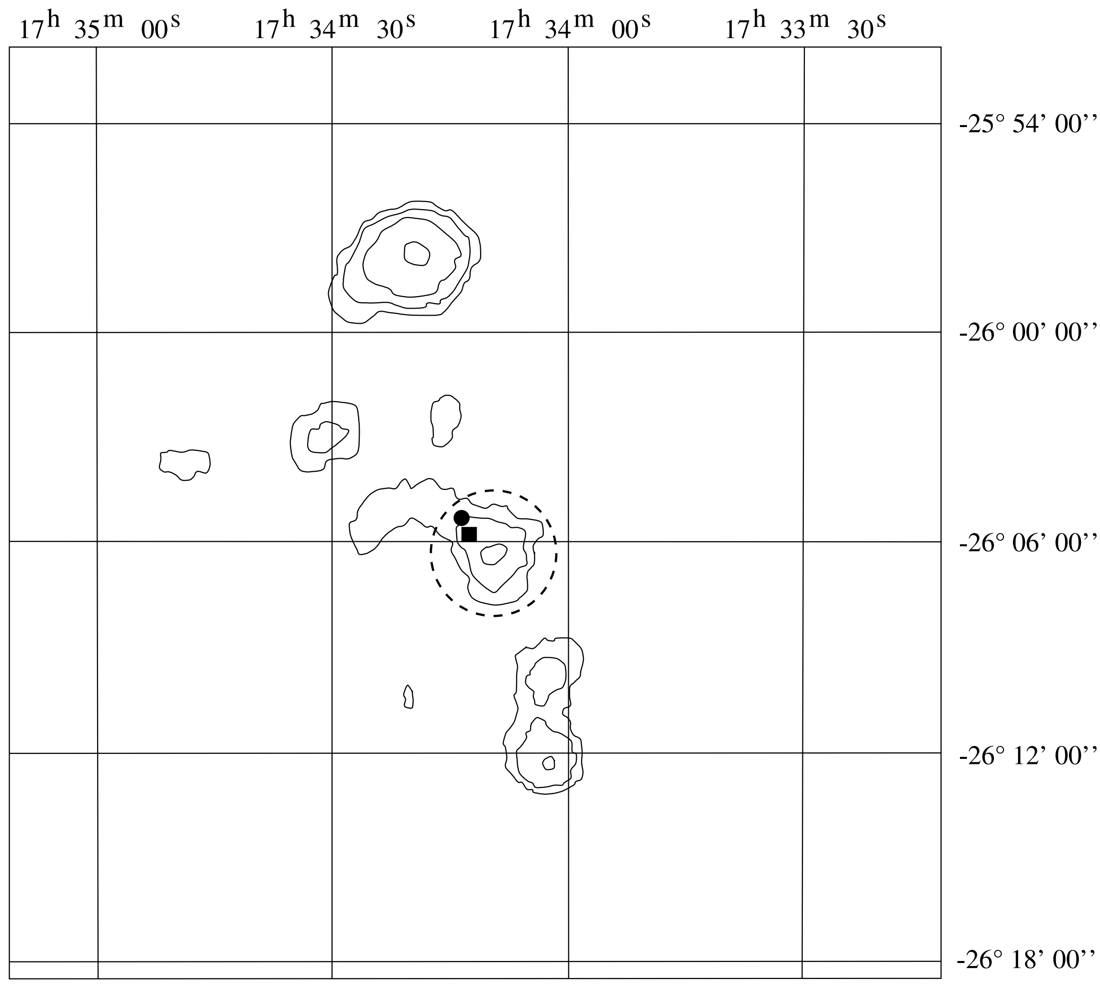

FIG. 1.—Plot of the MECS FOV. The source we have detected close to the nominal position of KS 1731−260 is shown at the center. There, the dashed line represents the 1'.8 circular region from which the data have been extracted. The positions of the sources identified in the *Chandra* observation are also shown, i.e., KS 1731−260 (*circle*) and the 2MASS star (*square*).

body model. In the following, we adopt as a reasonable estimate for the source luminosity in quiescence $L_q \lesssim 1 \times 10^{33}$ ergs s^{-1}.

At the beginning of 2001 August, KS 1731−260 was observed, still in its quiescent state (according to the ASM light curve), at 1.4 GHz with the Parkes radio telescope to search for radio pulses. Taking into account the possibility, suggested by Muno et al. (2000), that the NS belongs to an extremely narrow binary system with an orbital period of ∼1 hr, we subdivided the data into segments of 35 and 4 minutes. The analysis of longer segments allows us to reach a better sensitivity if the NS is in a wide orbit. On the other hand, when using shorter segments, the time of arrival of the radio pulses is not heavily affected by the strong Doppler effect caused by the orbital motion in a narrow binary system, which could reduce the coherence of the signal. We found that no radio signals with millisecond periods are present in the data above a flux limit of 0.21 mJy for the 35 minute integration time and above 0.60 mJy for the 4 minute integration time.

3. DISCUSSION

The 90 ks *BeppoSAX* observation of KS 1731−260 carried out on 2001 March 2–5 led to a detection of the source at a luminosity level of ∼10^{33} ergs s^{-1}. This is similar to the flux determined in a subsequent observation of the source carried out with *Chandra* on 2001 March 27 (Wijnands et al. 2001b). These results testify that the quiescent X-ray luminosity and spectrum of KS 1731−260 are close to those determined for other NS SXTs. We therefore assume that the X-ray spectrum of KS 1731−260 in quiescence is similar to that of Aql X-1 and Cen X-4 (see, e.g., Campana et al. 1998b), the best studied cases. The spectra of these two sources could be well fitted by a soft thermal component (blackbody temperature of ∼0.2 keV) plus a power-law component with a photon index $\Gamma \sim 1.5$. The blackbody component is usually interpreted as thermal emission from a pure hydrogen NS atmosphere (e.g., Rutledge et al. 1999, 2000), while the power-law component is thought to be due to residual accretion or the interaction of a pulsar wind with matter released by the companion star (see, e.g., Campana & Stella 2000, and references therein).

In the following, we discuss the properties of KS 1731−260 in relation to the different mechanisms that have been proposed to explain the quiescent X-ray emission of NS SXTs. In summary, there exist three sources of energy that are expected to produce X-ray luminosity in quiescence:

1. Residual accretion onto the NS surface at very low rates (e.g., Stella et al. 1994).

2. Rotational energy of the NS converted into radiation through the emission from a rotating magnetic dipole, a fraction of which can be emitted in X-rays (e.g., Possenti et al. 2002; Campana et al. 1998a, and references therein).

3. Thermal energy, stored in the NS during previous phases of accretion and released during quiescence (e.g., Brown, Bildsten, & Rutledge 1998; Colpi et al. 2001; Rutledge et al. 2001).

We compare the corresponding expectations with the measured upper limit on the X-ray luminosity. Note that the last process always has to be taken into account, as the source was recently active for more than 1 yr at a luminosity of $\sim 10^{37}$ ergs s^{-1} and frequently active, at comparable luminosities, since its discovery in 1989. Therefore, we first derive some constraints resulting from processes 1 and 2, and then we combine these with the constraint derived from process 3.

Some constraints for processes 1 and 2 can be derived if we assume that the coherent pulsations detected during the type I X-ray burst on 1996 July 14 (Smith et al. 1997) correspond to the NS spin. Indeed, the high degree of coherence ($\nu/\Delta\nu \gtrsim 900$) is compatible with broadening induced by the finite duration of the oscillations (~ 2 s). This strongly supports the interpretation of the frequency of these oscillations ($\nu = 523.92$ Hz) as the rotational frequency of the NS. Note that the frequency separation between the kilohertz QPOs in KS 1731−260 is ~ 260 Hz (Wijnands & van der Klis 1997), which might be interpreted as the spin frequency of the NS (Strohmayer et al. 1996; Miller, Lamb, & Psaltis 1998), while the burst frequency would be its first overtone in this case (see, however, Muno et al. 2000). For concreteness in the following, we assume the burst frequency as the NS spin frequency and discuss differences when needed.

It has been demonstrated that a rotating magnetic dipole in vacuum emits electromagnetic dipole radiation. Moreover, a wind of relativistic particles associated with magnetospheric currents along the field lines is expected to arise in a rotating NS (e.g., Goldreich & Julian 1969). Both of these processes, powered by the rotational energy of the NS, depend on the angle between the NS magnetic moment and the spin axis and compensate in such a way that the total energy emitted is nearly independent of this angle (Bhattacharya & van den Heuvel 1991). Thus, the bolometric luminosity of a rotating NS in vacuum can be calculated according to Larmor's formula, $L_{\rm bol} = (2/3c^3)\mu^2\omega^4$, where c is the speed of light, $\mu = B_s R_{\rm NS}^3$ (where B_s is the surface magnetic field at the magnetic equator and $R_{\rm NS}$ is the NS radius), and ω is the angular frequency of the NS. A small fraction of this luminosity is emitted in the radio band, probably as the result of electron accelerations in ultrastrong electric potentials (gaps). A still open question is the location of the accelerator (gap) in the outer magnetosphere, close to the light-cylinder radius ($r_{\rm LC} = cP/2\pi$, i.e., the radius at which an object corotating with the NS attains the speed of light), as proposed for the pulsar emission mechanism by Halpern & Ruderman (1993), or close to the magnetic cap, as originally proposed by Arons (1981) and Daugherty & Harding (1982). The observability of the radio emission can be strongly affected by the matter surrounding the NS. In particular, free-free absorption can strongly reduce the radio flux, especially at low radio frequencies (see, e.g., Burderi & King 1994; and more recently, D'Amico et al. 2001). However, independent of the observability of the radio pulsar, this radiative regime certainly occurs when the space surrounding the NS is free of matter up to $r_{\rm LC}$, and the pressure of this radiation can overcome the pressure of the accretion flow, thus preventing further accretion (see Ruderman, Shaham, & Tavani 1989; Illarionov & Sunyaev 1975). Therefore, in the following, we adopt the hypothesis that once the magnetospheric radius is outside the light-cylinder radius (and thus the space surrounding the NS up to the light cylinder is free of matter), the NS emits radiation according to Larmor's formula. In this case, irrespective of the amount of radiation emitted in the radio band and of its observability, we say, for shortness, that the radio pulsar is active.

As mentioned above, there are two possibilities: the first possibility, scenario 1, is that the magnetospheric radius is inside the light-cylinder radius and therefore the radio pulsar is off. In this case, for a nonzero NS magnetic field, we should have some matter flow toward the NS in order to keep the magnetospheric radius small enough. In this scenario, we again have two possibilities: (1a) the magnetospheric radius is inside the corotation radius (see below for a definition), so accretion onto the NS surface is possible; and (1b) the magnetospheric radius is outside the corotation radius (but still inside the light-cylinder radius), so the accretion onto the NS is centrifugally inhibited, but an accretion disk can still be present and emit X-rays. The other possibility, scenario 2, is that the magnetospheric radius is outside the light-cylinder radius and therefore the radio pulsar is on. In this case, X-ray emission can be produced by (2a) the reprocessing of part of the bolometric luminosity of the rotating NS (Larmor's radiation formula) into X-rays in a shock front; and (2b) the intrinsic X-ray emission of the radio pulsar.

Let us consider scenario 1, i.e., a nonzero accretion rate during the quiescent phase, and in particular scenario 1a. If the NS has an intrinsic magnetic field, we can estimate an upper limit on the NS magnetic moment. Note that a similar argument was applied to an *ASCA* observation of the Rapid Burster in quiescence by Asai et al. (1996). In that case it was also concluded that a highly magnetized and rapidly rotating NS can be excluded. The matter accreting onto the NS forms an accretion disk whose inner radius is truncated at the magnetosphere by the interaction of the accretion flow with the magnetic field of the NS. In this case, the magnetospheric radius r_m is a fraction $\phi \lesssim 1$ (an expression for ϕ can be found in Burderi et al. 1998;[11] for $L \sim 10^{33}$ ergs s^{-1}, we get $\phi \sim 0.2$) of the Alfvén radius $R_{\rm A}$, defined as the radius at which the energy density of the (assumed dipolar) NS magnetic field equals the kinetic energy density of the spherically accreting (free-falling) matter,

$$R_{\rm A} = 2.23 \times 10^6 R_6^{-2/7} m^{1/7} \mu_{26}^{4/7} \epsilon^{2/7} L_{37}^{-2/7} \ {\rm cm} \qquad (1)$$

(see, e.g., Hayakawa 1985), where R_6 is the NS radius $R_{\rm NS}$ in units of 10^6 cm, m is the NS mass in solar masses, μ_{26} is the NS magnetic moment in units of 10^{26} G cm^3, ϵ is the ratio between the specific luminosity and the specific binding energy ($L = \epsilon GM\dot{M}/R_{\rm NS}$, where G is the gravitational con-

[11] The expression is $\phi = 0.21\alpha^{4/15} n_{0.615}^{8/27} m^{-142/945} [(L_{37}/\epsilon)^{8/7} R_6^{8/7} \mu_{26}^{5/7}]^{4/135}$; see the text for the definition of the symbols.

stant, M is the NS mass, and $\dot{M}$ is the accretion rate), and L_{37} is the accretion luminosity in units of 10^{37} ergs s^{-1}. Actually, accretion onto a spinning, magnetized NS is centrifugally inhibited once the magnetospheric radius is outside the corotation radius, the radius at which the Keplerian frequency of the orbiting matter is equal to the NS spin frequency,

$$r_{co} = 1.5 \times 10^6 P_{-3}^{2/3} m^{1/3} \text{ cm} , \quad (2)$$

where P_{-3} is the spin period in milliseconds. The condition to allow accretion then reads $r_m/r_{co} \leq 1$. This requires

$$\mu_{26} \leq 0.5\phi^{-7/4} R_6^{1/2} \epsilon^{-1/2} L_{37}^{1/2} m^{1/3} P_{-3}^{7/6} . \quad (3)$$

Adopting our upper limit $L_{37} = 10^{-4}$ for the quiescent luminosity, we obtain $\mu_{26} \leq 0.28 m^{1/3}$ for $P_{-3} = 1.91$ ($\mu_{26} \leq 0.63 m^{1/3}$ for $P_{-3} = 3.82$), where we have assumed $\epsilon = R_6 = 1$ and $\phi \simeq 0.2$.

If the magnetospheric radius is outside the corotation radius and still inside the light-cylinder radius (scenario 1b), the accretion is centrifugally inhibited, but the disk can still emit X-rays. This will increase the upper limit on the magnetic field derived above because in the propeller regime, the system will be underluminous by a factor of $\epsilon_{prop} = R_{NS}/(2r_{disk})$, for a given accretion rate. In this case, the maximum accretion rate for a given luminosity occurs when the efficiency factor ϵ is minimum. This occurs when the inner disk radius is the furthest from the NS surface without allowing the switch-on of the radio pulsar, i.e., for $r_{disk} \lesssim r_{LC}$. Assuming $r_m = r_{LC}$ and taking as an upper limit on $\dot{M}$ the condition $L_q = L_{disk}(r_{LC}) = \epsilon_{prop} G M \dot{M}/R_{NS}$, with $\epsilon_{prop} = R_{NS}/(2r_{LC})$, we can calculate the upper limit on the magnetic moment in this case,

$$\mu_{26} \leq 11.7\phi^{-7/4} L_{37}^{1/2} P_{-3}^{9/4} m^{-1/4} , \quad (4)$$

where we have assumed $R_6 = 1$. This gives $\mu_{26} \leq 8.4 m^{-1/4}$ for $P_{-3} = 1.91$ (and $\mu_{26} \leq 39.8 m^{-1/4}$ for $P_{-3} = 3.82$), where we have assumed $L_{37} = 10^{-4}$ for the quiescent luminosity and $\phi \simeq 0.2$ (in fact, as $\phi \propto \epsilon_{prop}^{-32/945}$, $\phi = 0.18 \simeq 0.2$ is also appropriate in the propeller case).

Let us now consider scenario 2. If there is no accretion in quiescence or the magnetospheric radius falls outside the light-cylinder radius, we expect the radio pulsar to switch on. The pulsar radiation pressure may overcome the pressure of the accretion disk, thus determining the destruction of the disk and the ejection of matter from the system (see Burderi et al. 2001). However, there is the possibility that a fraction η of this power can be converted into X-rays in a shock front between the relativistic pulsar wind and the circumstellar matter (scenario 2a). Typical values for η are in the range ~0.01–0.1, as also deduced from observations of the 47 ms binary radio pulsar PSR B1259−63 (e.g., Campana et al. 1998a; Tavani 1991; Kaspi et al. 1995; Grove et al. 1995). In this case, $\eta L_{rad} \lesssim L_q$, or

$$\mu_{26} \leq 5.1 L_{37}^{1/2} P_{-3}^2 \eta^{-1/2} . \quad (5)$$

In our case, assuming the minimum value for the efficiency in the conversion of the rotational energy into X-rays, $\eta = 0.01$, which implies the highest value for the magnetic moment, we get $\mu_{26} \leq 1.9$ for $P_{-3} = 1.91$ (and $\mu_{26} \leq 7.5$ for $P_{-3} = 3.82$). Let us consider the possibility that part of the spin-down energy loss is directly emitted in X-rays (scenario 2b). Indeed, about 40 out of ~1400 known radio pulsars have been detected in the X-ray range so far. In this case, a correlation has been observed between the X-ray and spin-down luminosities (e.g., Becker & Trümper 1997; Possenti et al. 2002, and references therein). Considering the empirical relation derived by Possenti et al. (2002), analyzing a sample of 37 pulsars, between the 2–10 keV luminosity L_{37} and the rate of spin-down energy loss L_{rad},

$$L_{37} = 2.51 \times 10^{-52} L_{rad}^{1.31} , \quad (6)$$

we can again calculate an upper limit on the magnetic moment in the case of KS 1731−260, which gives $\mu_{26} \leq 8.7$ for $P_{-3} = 1.91$ (and $\mu_{26} \leq 34.6$ for $P_{-3} = 3.82$).

In the last two cases, the X-ray emission is expected to be nonthermal (a power-law spectrum could be appropriate). Interestingly, Wijnands et al. (2001b) found that the *Chandra* spectra of KS 1731−260 in quiescence could be equally well fitted by a blackbody or a power law plus a blackbody (although the power law is not statistically required). In this second case, one might think that the thermal component arises from the NS surface and the nonthermal power law is associated with the shock emission discussed above. Indeed, according to the results of the spectral deconvolution of Wijnands et al. (2001b), the fraction of the total luminosity emitted in the power law is ~15%, small as compared to the total luminosity. However, because of the low statistics, the spectral deconvolution is not secure, and in the case of our *BeppoSAX* observation, no statistically significant spectral analysis is possible. For this reason, in deriving our upper limits on the magnetic-moment strength in these scenarios, we have adopted the very conservative assumption that the whole flux detected by *BeppoSAX* can be ascribed to the nonthermal emission.

An upper limit on the NS magnetic field can also be derived from the upper limit on the radio pulsed emission from KS 1731−260. Radio observations of KS 1731−260, taken at the Parkes radio telescope while the system was in quiescence, showed that the upper limit on the flux of pulsed radio emission is 0.21 mJy using a 35 minute integration time and 0.60 mJy using a 4 minute integration time. Equating the rotational energy lost by a magnetized NS with its magnetic dipole radiation, we obtain

$$P\dot{P} = 9.75 \times 10^{-24} \mu_{26}^2 I_{45}^{-1} , \quad (7)$$

where P and $\dot{P}$ are respectively the period of the radio pulsar and its derivate, and I_{45} is the NS moment of inertia in units of 10^{45} g cm^2. Proszynski & Przyibician (1985), using a sample of 275 pulsars, found an empirical relation between the observed 400 MHz luminosity L_{400} and the pulsar parameters,

$$\log(L_{400}) = \frac{1}{3}\log\left(\frac{\dot{P}_{-15}}{P^3}\right) + A , \quad (8)$$

where L_{400} is expressed in mJy kpc^2, $\dot{P}_{-15}$ is in units of 10^{-15} s s^{-1}, and $A = 1.1$. Kulkarni, Narayan, & Romani (1990) found that the same relation could easily fit a sample of 11 recycled binary pulsars. For KS 1731−260, assuming a distance of 7.0 kpc and a spectral index $\alpha = 1.7$, typical of millisecond pulsars, we obtain for the 400 MHz luminosity an upper limit of 88.47 mJy kpc^2 in the case of a 35 minute integration and of 250.25 mJy kpc^2 in the case of a 4 minute integration. Using these values and combining equations (7) and (8), we can again calculate an upper limit to the magnetic field of KS 1731−260. If the NS is in a wide orbit, i.e., if the phase shifts introduced by the Doppler effect are negligible over an integration time of 35 minutes, we obtain an upper limit of $\mu_{26} \leq 0.68$ for $P_{-3} = 1.91$ (and $\mu_{26} \leq 2.7$ for $P_{-3} = 3.82$), assuming $I_{45} = R_6 = 1$. If instead the NS in KS 1731−260 belongs to a narrow binary system, and then the 4 minute observations are more appropriate, we obtain $\mu_{26} \leq 3.1$ for $P_{-3} = 1.91$ (and $\mu_{26} \leq 12.6$ for $P_{-3} = 3.82$). Note, however, that free-free absorption from matter surrounding the system (expected if the mass loss from the companion proceeds at some level during the quiescent phase; see Burderi et al. 2001 for a detailed discussion of this possibility in transient systems) can efficiently hamper the detection of the pulsed radio emission from an active radio pulsar.

We now consider process 3, i.e., the thermal emission from the NS. The theory of deep crustal heating was first developed by Haensel & Zdunick (1990). It was pointed out by Brown et al. (1998) that this scenario was relevant to accreting NSs in transient systems, and could contribute to the emission at low luminosities. This scenario applies if the system has time to reach a steady state, in which the heat deposited during short and frequent outbursts in the NS is equal to the luminosity radiated in quiescence. Colpi et al. (2001) have explored the thermal evolution of a NS undergoing episodes of accretion, lasting for a time $t_{\rm out}$, separated by periods of quiescence, lasting $t_{\rm rec}$, in the hypothesis that the thermal luminosity in quiescence is dominated by emission from the hot NS core, with which the crust and atmosphere of the NS are in thermal equilibrium. Adopting an outburst luminosity of 10^{37} ergs s^{-1} and a quiescent luminosity of 10^{33} ergs s^{-1}, this model predicts a ratio of the recurrence time $t_{\rm rec}$ to the outburst time $t_{\rm out}$ of $\sim$70 for a 1.4 $M_\odot$ NS and less than 4 for a NS more massive than 1.7 $M_\odot$. A $t_{\rm rec}/t_{\rm out} \sim 70$ would imply that, on average, the total time the source should spend in outburst in 13 yr (i.e., since its discovery) should be about 2 months. This is in conflict with the time history of this source and the fact that the last outburst episode observed by the ASM lasted much more than 1 yr. As already pointed out by Wijnands et al. (2001b), we are therefore left with two possibilities: (1) we are witnessing a peculiar period of hyperactivity of the source, which will be followed by a much longer (up to 1000 yr) quiescent phase; (2) the NS in this system is quite massive, in agreement with the expectation of the standard conservative recycling scenario (e.g., Bhattacharya & van den Heuvel 1991) that the NS has accreted a significant amount of mass and has been spun up to a millisecond spin period.

However, Rutledge et al. (2001) found that since KS 1731−260 has recently experienced an extremely long outburst, the thermal luminosity in quiescence could be dominated by emission from the heated NS crust out of thermal equilibrium with the core. Indeed, the prediction of the quiescent luminosity from the cooling-crust model agrees (within a factor of a few) with the observed bolometric luminosity in quiescence. In this case, the model above cannot be applied to the system, given that the core might be much cooler than indicated by the thermal luminosity in quiescence. This implies that the presence of a massive NS is not required to explain the behavior of this system and that the estimated long outburst recurrence timescale mentioned above should be considered as a lower limit. Rutledge et al. (2001) also calculated the expected thermal evolution of the crust, which should cool in 1–30 yr, and therefore the time evolution of the quiescent luminosity for different crustal conductivities and cooling processes, showing that a monitoring of this source can provide valuable information on the crust and core microphysics.

A further constraint on the magnetic moment can be derived considering that the NS spin period must be longer than the equilibrium spin period, namely, the Keplerian period at the magnetospheric radius:

$$P_{\rm eq} = 1.81 \times 10^{-3} \phi^{3/2} R_6^{-3/7} \mu_{26}^{6/7} \epsilon^{3/7} L_{37}^{-3/7} m^{-2/7} \text{ s} . \quad (9)$$

Adopting $\phi = 0.2$ and an outburst luminosity of $L_{37} = 1$ (i.e., the average luminosity observed with ASM and previous missions when the source was detected), we obtain $\mu_{26} \leq 16.4 m^{1/3}$ for $P_{-3} = 1.91$ (and $\mu_{26} \leq 36.8 m^{1/3}$ for $P_{-3} = 3.82$). As KS 1731−260 is a transient source, it is possible that during quiescence the NS enters a propeller phase, during which an efficient torque could spin down the NS far from the equilibrium period defined above. In this case, the magnetic moment is significantly *less* than the value derived in this paragraph. On the other hand, if the propeller phases are infrequent and/or the spin-down torque is inefficient, the NS is expected to be in spin equilibrium and $\mu_{26} = 16.4 m^{1/3}$ ($\mu_{26} = 36.8 m^{1/3}$).

From the discussion above, we conclude that in any case, the NS magnetic field is most probably less than $\sim 10^9$ G and less than $\sim 4 \times 10^9$ G in the worst case.

Let us finally discuss the consequences of the spin equilibrium constraint when applied to the proposed scenarios in quiescence. In fact, if we consider the case that the NS in KS 1731−260 is quite massive, the amount of mass accreted, $\gtrsim 0.3\ M_\odot$, is sufficient in principle to spin up the NS to below 1 ms for soft or moderately stiff equations of state for the NS matter and below 1.5 ms even for the stiffest equations of state (see Burderi et al. 1999). Therefore, we can say the following about the different scenarios:

1a. The NS in quiescence accretes matter onto its surface at very low rates. In this case, $\mu_{26} \leq 0.28 m^{1/3}$ ($\mu_{26} \leq 0.63 m^{1/3}$). This, compared with the spin equilibrium constraint, i.e., $\mu_{26} \leq 16.4 m^{1/3}$ ($\mu_{26} \leq 36.8 m^{1/3}$), implies that the NS is far from spinning at equilibrium, i.e., propeller phases must be frequent and the spin-down torque very effective, although this quiescent phase does not correspond to a propeller.

1b. The NS in quiescence is in a propeller phase. In this case, $\mu_{26} \leq 8.4 m^{-1/4}$ ($\mu_{26} \leq 39.8 m^{-1/4}$). This, compared with the spin equilibrium constraint $\mu_{26} \leq 16.4 m^{1/3}$ ($\mu_{26} \leq 36.8 m^{1/3}$), indicates that the NS is compatible with spinning close to the equilibrium. In this case, propeller phases must be rare (although the present quiescent phase does correspond to a propeller) and/or the spin-down torque not very effective.

2a. The NS in quiescence is not accreting matter and the radio pulsar is active; a fraction of the power emitted by the rotating NS is converted into X-rays in a shock front between the emerging radiation and the circumstellar matter. In this case, $\mu_{26} \leq 1.9$ ($\mu_{26} \leq 7.5$). This, compared with the spin equilibrium constraint, implies that the NS is far from spinning at equilibrium, i.e., again, propeller phases must be frequent and the spin-down torque very effective, although this quiescent phase does not correspond to a propeller.

2b. The NS in quiescence is not accreting matter and the radio pulsar is active; in this case, the fraction of power emitted by the rotating NS that is converted into X-rays in a shock front between the emerging radiation and the circumstellar matter is negligible, and the X-ray emission is the intrinsic emission from the rotating NS. In this case, $\mu_{26} \leq 8.7$ ($\mu_{26} \leq 34.6$). This implies that the NS is compatible with spinning close to the equilibrium, i.e., propeller phases must be rare (indeed, the present quiescent phase does not correspond to a propeller) and/or the spin-down torque not very effective.

In conclusion, scenarios 1b and 2b seem to be the most reasonable, and both indicate that the NS is compatible with spinning close to the equilibrium period.

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REFERENCES

Arons, J. 1981, ApJ, 248, 1099
Asai, K., Dotani, T., Kunieda, H., & Kawai, N. 1996, PASJ, 48, L27
Barret, D., Motch, C., & Predehl, P. 1998, A&A, 329, 965
Becker, W., & Trümper, J. 1997, A&A, 326, 682
Bhattacharya, D., & van den Heuvel, E. P. J. 1991, Phys. Rep., 203, 1
Boella, G., et al. 1997, A&AS, 122, 327
Brown, E. F., Bildsten, L., & Rutledge, R. E. 1998, ApJ, 504, L95
Burderi, L., di Salvo, T., Robba, N. R., del Sordo, S., Santangelo, A., & Segreto, A. 1998, ApJ, 498, 831
Burderi, L., & King, A. R. 1994, ApJ, 430, L57
Burderi, L., Possenti, A., Colpi, M., Di Salvo, T., & D'Amico, N. 1999, ApJ, 519, 285
Burderi, L., et al. 2001, ApJ, 560, L71
Campana, S., Colpi, M., Mereghetti, S., Stella, L., & Tavani, M. 1998a, A&A Rev., 8, 279
Campana, S., & Stella, L. 2000, ApJ, 541, 849
Campana, S., Stella, L., Mereghetti, S., Colpi, M., Tavani, M., Ricci, D., Dal Fiume, D., & Belloni, T. 1998b, ApJ, 499, L65
Colpi, M., Geppert, U., Page, D., & Possenti, A. 2001, ApJ, 548, L175
D'Amico, N., Lyne, A. G., Manchester, R. N., Possenti, A., & Camilo, F. 2001, ApJ, 548, L171
Daugherty, J. K., & Harding, A. K. 1982, ApJ, 252, 337
Frontera, F., Costa, E., dal Fiume, D., Feroci, M., Nicastro, L., Orlandini, M., Palazzi, E., & Zavattini, G. 1997, A&AS, 122, 357
Goldreich, P., & Julian, W. H. 1969, ApJ, 157, 869
Grove, J. E., et al. 1995, ApJ, 447, L113
Haensel, P., & Zdunik, J. L. 1990, A&A, 227, 431
Halpern, J. P., & Ruderman, M. 1993, ApJ, 415, 286
Hayakawa, S. 1985, Phys. Rep., 121, 317
Illarionov, A. F., & Sunyaev, R. A. 1975, A&A, 39, 185
Kaspi, V., et al. 1995, ApJ, 453, 424
Kulkarni, S. R., Narayan, R., & Romani, R. W. 1990, ApJ, 356, 174
Manzo, G., Giarrusso, S., Santangelo, A., Ciralli, F., Fazio, G., Piraino, S., & Segreto, A. 1997, A&AS, 122, 341
Miller, M. C., Lamb, F. K., & Psaltis, D. 1998, ApJ, 508, 791
Muno, M. P., Fox, D. W., Morgan, E. H., & Bildsten, L. 2000, ApJ, 542, 1016
Parmar, A. N., et al. 1997, A&AS, 122, 309
Possenti, A., Cerutti, R., Colpi, M., & Mereghetti, S. 2002, A&A, in press (astro-ph/0109452)
Proszyhski, M., & Przybycien, D. 1985, in Birth and Evolution of Neutron stars: Issues Raised by Millisecond Pulsars, ed. S. P. Reynolds & D. R. Stinebring (Green Bank: NRAO), 151
Ruderman, M., Shaham, J., & Tavani, M. 1989, ApJ, 343, 292
Rutledge, R. E., Bildsten, L., Brown, E. F., Pavlov, G. G., & Zavlin, V. E. 1999, ApJ, 514, 945
———. 2000, ApJ, 529, 985
Rutledge, R. E., Bildsten, L., Brown, E. F., Pavlov, G. G., Zavlin, V. E., & Ushomirsky, G. 2001, ApJ, submitted (astro-ph/0108125)
Smith, D. A., Morgan, E. H., & Bradt, H. 1997, ApJ, 479, L137
Stella, L., Campana, S., Colpi, M., Mereghetti, S., & Tavani, M. 1994, ApJ, 423, L47
Strohmayer, T. E., Swank, J. H., & Zhang, W. 1999, Nucl. Phys. B Supl., 69, 129
Strohmayer, T. E., Zhang, W., Swank, J. H., Smale, A., Titarchuk, L., Day, C., & Lee, U. 1996, ApJ, 469, L9
Sunyaev, R. 1989, IAU Circ. 4839
Sunyaev, R., et al. 1990, Soviet Astron. Lett., 16, 59
Tavani, M. 1991, ApJ, 379, L69
Wijnands, R., Groot, P. J., Miller, J. J., Morkwardt, C., Lewin, W. H. G., & van der Klis, M. 2001a, Astron. Telegram 72
Wijnands, R., Miller, J. M., Markwardt, C., Lewin, W. H. G., & van der Klis, M. 2001b, ApJ, 560, L159
Wijnands, R. A. D., & van der Klis, M. 1997, ApJ, 482, L65