INDIRECT EVIDENCE OF AN ACTIVE RADIO PULSAR IN THE QUIESCENT STATE OF THE TRANSIENT MILLISECOND PULSAR SAX J1808.4−3658

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ABSTRACT

Millisecond radio pulsars are neutron stars that have been spun up by the transfer of angular momentum during the low-mass X-ray binary phase. The transition from an accretion-powered pulsar to a rotation-powered pulsar takes place on evolutionary timescales at the end of the accretion process; however, it may also occur sporadically in systems undergoing transient X-ray activity. We have obtained the first optical spectrum of the low-mass transient X-ray pulsar SAX J1808.4−3658 in quiescence. Similar to the black widow millisecond pulsar B1957+20, this X-ray pulsar shows a large optical modulation at the orbital period due to an irradiated companion star. Using the brightness of the companion star as a bolometer, we conclude that a very high irradiating luminosity, a factor of ∼100 larger than directly observed, must be present in the system. This most likely derives from a rotation-powered neutron star that resumes activity during quiescence.

Subject headings: accretion, accretion disks — binaries: close — stars: neutron

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1.INTRODUCTION

SAX J1808.4−3658 was the first-discovered low-mass X-ray binary (LMXB) transient showing coherent pulsations. This confirmed unambiguously the long-sought connection between LMXBs and millisecond radio pulsars (Bhattacharya & van den Heuvel 1991; Tauris & van den Heuvel 2004). The detection of coherent X-ray pulsations during outbursts testifies that the neutron star possesses a magnetic field of $B \approx 10^{5}$–$10^{6}$ G, sufficient for a small magnetosphere to form (Psaltis & Chakrabarty 1999; Menna et al. 2003; Di Salvo & Burderi 2003).

Unlike persistent LMXBs, SAX J1808.4−3658 is a transient system; i.e., it is active in X-rays only for short intervals lasting a few months (outbursts) followed by quiescent periods of years.

During quiescence, LMXB transients are very faint in X-rays (5–6 orders of magnitude less than in outburst), usually with luminosities of $10^{32}$–$10^{33}$ ergs s$^{-1}$. Transient systems, therefore, represent a unique laboratory for the study of compact objects in accretion regimes that are inaccessible to persistent sources. Most neutron star transients are characterized by a quiescent X-ray spectrum consisting of a soft component, usually ascribed to the cooling neutron star that has been heated during outbursts (Brown et al. 1998; Rutledge et al. 1999), and a hard power-law tail (with photon index $\Gamma \sim 1$–2) the nature of which is still debated (Campana & Stella 2000). Several mechanisms have been put forward to explain these spectral components, ranging from accretion disks (in different flavors such as advection-dominated or convection-dominated disks, disks stopping at the magnetosphere, etc.; Narayan et al. 1997; Blanford & Begelman 1999; Igumenshchev et al. 2003) to emission from the interaction between the relativistic wind from a reactivated radio pulsar and matter outflowing from the companion star (Stella et al. 1994; Campana et al. 1998b).

$\gamma$-ray pulsations were first detected in the optical from the interaction between the relativistic wind from the neutron star and the matter surrounding it (Campana et al. 2001). The light curve in outburst and quiescence is modulated at the orbital period, and it is in antiphase with the X-ray light curve, likely indicating that irradiation of the companion star plays a crucial role in spite of the low X-ray luminosity. This is unlike other quiescent transients. The mass function derived from X-ray data ($4 \times 10^{-5} M_{\odot}$; Chakrabarty & Morgan 1998) and the requirement that the companion fills its Roche lobe led to the conclusion that it must be a rather low mass star, possibly a brown dwarf (Bildsten & Chakrabarty 2001). A white dwarf companion is ruled out because it would not fill its Roche lobe. Homer et al. (2001) proposed that the bulk of the optical emission in quiescence arises from the internal energy release of a remnant disk and the orbital modulation from the varying contribution of the heated face of the companion star. Burderi et al. (2003) noted that the required irradiating luminosity needed to match the optical flux, however, is a factor of 10–50 higher than the quiescent X-ray luminosity of SAX J1808.4−3658. These authors proposed an alternative scenario in which the irradiation is due to the rotational energy emitted in the form of a relativistic particle wind from the fast spinning neutron star, which switched to the rotation-powered regime during quiescence. Their results are in agreement with the weak constraints from the optical magnitudes by Homer et al. (2001).

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2. DATA ANALYSIS

Here we present indirect evidence of an active radio pulsar in SAX J1808.4−3658 during quiescence with the first optical spectra and I band photometry of SAX J1808.4−3658. These data were obtained with the ESO-VLT (UT4 Yepun) during two half-nights on 2002 July 12–13. We carried out I-band photometry with 3 minute exposures with FORS2 (pixel size of 0′126 pixel−1 and a field of view of 6′.8 × 6′.8) over one orbital period. Spectroscopy of the same target was performed using the low-resolution grism 600RI (centered at 6780 Å with a resolution of 55 Å mm−1) covering 5120–8450 Å and a 1′′ slit with 3 minute spectra over four orbital periods. Data reduction was done in MIDAS to remove the bias level and flat field.

The region around the optical companion of SAX J1808.4−3658 is crowded, and poor seeing conditions complicated the analysis (varying between 1′.5 and 2′). We take advantage of previous ESO-VLT images (obtained during quiescence in 1999 with seeing ∼0′.5) to deblend our data (these magnitudes were V = 21.82 ± 0.03, R = 21.63 ± 0.04, and I = 21.08 ± 0.04). Our I photometry shows a dimmer source (I = 21.5 ± 0.1) and a clear modulation at the 2.01 hr orbital period with a semiamplitude 0.2 ± 0.04 mag (65% in flux; see Figs. 1 and 2). We also recalculated the modulation semiamplitude in V (0.13 ± 0.06) and R (0.39 ± 0.09) using the Homer et al. (2001) data. The I-band light curve shows a clear maximum at phase 0.52 ± 0.05 and a single minimum at phase 0.02 ± 0.05 (based on the precise X-ray ephemerides of Chakrabarty & Morgan 1998). This is a clear indication of emission from an irradiated companion (e.g., Charles & Coe 2004), and it argues against emission from the impact point between the gas stream from the companion and an accretion disk (the hot spot) since this has a maximum at phase 0.8–0.9.

We obtained spectra at 3 minute intervals over four orbital periods. We selected spectra taken with seeing better than 1′.6 (due to poor seeing conditions), collecting a total of 51 minutes of good data. Wavelength calibrations used HeArNe arc lamp observations. Second-order flexure effects were corrected using night-sky emission lines. This correction was always less than
0.3 Å. Spectra were corrected for slit losses according to Diego
(1985). We also account for the contaminating stars, estimating
their relative contribution in a 1″ slit on the good-seeing VLT images
and interpolating to the spectral range. Errors were
tracked along these processes resulting in a 0.1 mag error. A
weak Hα emission line is visible in the spectrum (equivalent
width EW = 10.3 ± 3.7 Å, 68% confidence level, and
FWHM = 44.0 ± 6.3 Å; see insert in Fig. 1).

3. MODELING THE DATA

We first checked that at the time of our observations, the source
was in quiescence. A Rossi X-Ray Timing Explorer (RXTE)
pointed observation, performed 15 days before the optical ob-
servations, provided a 3 σ upper limit of \( \sim 10^{35} \) ergs s\(^{-1}\) (0.5–
10 keV). Similar limits are provided by the Galactic bulge scan
performed by RXTE (nearest observation on 2002 July 10;
Swank & Markwardt 2002). While these limits are not particu-
larly constraining, they are sufficient to exclude that the source
was in outburst (note that an outburst started 3 months later;
Wijnands et al. 2003).

Since SAX J1808.4–3658 was in quiescence, what is the
cause of the optical emission? Likely candidates are emission
from the companion star and/or the disk. In order to fit within
the Roche lobe of a 2.01 hr binary, the companion mass has to
be less than 0.17 \( M_\odot \). In the model of Bildsten & Chakrabarty
(2001), the most likely companion is a 0.05 \( M_\odot \) brown dwarf
bloated by irradiation to fill its Roche lobe (0.13 \( R_\odot \)). The max-
imum intrinsic optical luminosity from the companion for any
of the models by Bildsten & Chakrabarty (2001) is \( \sim 3 \times 10^{31} \)
ergs s\(^{-1}\) (corresponding to a star temperature of 4800 K for
a distance of 2.5 kpc). This is too low a luminosity to account
for the observed optical flux, which is a factor of greater than
10 brighter. We therefore turn to the accretion disk as a possible
source. Assuming that the quiescent X-ray luminosity is pow-
ered by accretion, we can infer the expected mass inflow rate
and derive the corresponding optical luminosity (including ir-
radiation), which fails to account for what we see by more than
a factor of 100. Disk models may be envisaged with a much
higher mass accretion rate together with a truncation radius (fine-)
tuned to avoid optical and soft X-ray violation of ob-
served data. However, these kinds of models still require some
additional ingredient to explain the large optical phase mod-
ulation. The emission from the pulsar could itself extend to the
optical, and extrapolation of the power-law X-ray flux (assum-
ing the XMM-Newton observation found the X-rays in a similar
state) could account for about 30% of the optical luminosity.
But this also could not explain the observed orbital phase mod-
ulation.

It is instructive to compare the properties of SAX
J1808.4–3658 with those of the black widow pulsar PSR
B1957+20 (Fruchter et al. 1988), which consists of a 1.6 ms
radio pulsar irradiating its white dwarf companion (orbital pe-
riod of 9.16 hr) with a rotational energy of \( 10^{39} \) ergs s\(^{-1}\). X-
rays and γ-rays are generated in an interbinary shock front,
which causes ablation and heating of the companion (Phinney
et al. 1988; Arons & Tavani 1994). An X-ray nebula has re-
cently been revealed around PSR B1957+20 confirming this
scenario (Stappers et al. 2003), and the orbital modulation is
large with an \( R \)-band semiamplitude of greater than 4 mag
(Callanan et al. 1995). A similar system is the eclipsing mil-
isecond radio pulsar PSR J2051–0827, consisting of a 4.5 ms
pulsar orbiting its very low mass companion (\( \sim 0.03 \) \( M_\odot \)) every
2.4 hr (Stappers et al. 1996). Radio eclipses as well as an
\( \sim 5.3 \) mag optical modulation have been observed in PSR
J2051–0827 (Stappers et al. 2001); however, no X-ray obser-
vations are available.

Inspired by this analogy and following Burderi et al. (2003),
we now attempt to account for the optical and X-ray spectra
(even if not close in time) as well as the \( V, R, \) and \( I \) modulations
of SAX J1808.4–3658 with an irradiated star plus the contribu-
tion of the shock front. We fitted the data by using the ir-
radiating luminosity (\( L_{\text{irr}} \)), the fractional luminosity difference
between the heated and the cold face of the companion (\( j \)),
and interstellar absorption (\( A_v \)) as free parameters (e.g., Chak-
rabarty 1998). We obtain a good fit to all the available data
(reduced \( \chi^2 = 0.7 \) with 57 degrees of freedom; see Fig. 1).
In particular, the required irradiating luminosity is
\( L_{\text{irr}} = (4.3^{+1}_{-1}) \times 10^{33} \) ergs s\(^{-1}\) (90% confidence level for three free pa-
rameters; i.e., \( \Delta \chi^2 = 6.3 \)). The best-fit fraction is
\( f = 0.65 \pm 0.10 \) resulting in temperature difference at the two faces
of the companion star of about 1000 ± 300 K. This temperature
difference is similar to the one observed in PSR J2051–0827.
The amplitude modulation of SAX J1808.4–3658 is instead
smaller than in the case of PSR J2051–0827 and PSR
B1957+20. This could be due to some remaining contamination
due to our deblending process, or it could be an inclination effect.
For the most strongly modulated PSR J1957+20, the inclination is
\( \sim 70^\circ \), PSR J2051–0827 has an inclination of \( \sim 40^\circ \).

The estimated absorption is \( A_v = 1.0 \pm 0.5 \), in line with
previous estimates. Optical emission from the shock front ac-
counts for about 15% of the total emission.\(^{3}\) In the fit, we
assumed that all the irradiating luminosity is reemitted by the
star. Therefore, the irradiating luminosity we derived represents
only a lower limit since a relativistic particle wind could have
rather different effects from those of X-ray irradiation in terms
of effective albedo. Moreover, we note that evidence of this
large irradiating luminosity comes from the equivalent width
of the Hα line. If the line comes from reprocessing, one can
roughly infer an irradiating luminosity of \( \sim 3 \times 10^{33} \) ergs s\(^{-1}\).
This can be estimated by taking the line flux and increasing it
by the fraction of emitted flux intercepted by the star
(\( R^2/4a^2 \), with \( R \), the companion star radius taken to be
equal to the Roche lobe radius and \( a \) the orbital separation) and
by the fraction of energy reemitted in Hα (e.g., Hynes et al. 2002).
Here we assumed a conservative value of 0.3 (see the discus-
sion in Hynes et al. 2002).

4. CONCLUSIONS

The required irradiating luminosity is in all cases large
\( (\sim 4 \times 10^{33} \) ergs s\(^{-1}\)), indeed much larger than the observed X-
ray luminosity in quiescence; neither accretion-driven X-rays
nor the intrinsic luminosity of the companion star or disk are
able to account for it (see also Burderi et al. 2003). The only
source of energy available within the system is then the ro-
tational energy of the neutron star. In order to have such a large
spin-down luminosity, one needs a neutron star magnetic field
\( B \sim 6 \times 10^{13} \) G (the companion star albedo might be larger

\(^{3}\) The conversion efficiency of rotational energy into X-rays for SAX
J1808.4–3658 is \( \approx 10^{-5} \), a factor of 10 higher than PSR 1957+20 (Stappers et al. 2003), as expected due to geometrical reasons.

\(^{4}\) We fitted our data with an irradiated star plus the extrapolation to the
optical of the X-ray tail. The presence of a disk is not required by our fit. We
tried in any case to fit with an irradiated star plus a disk model, finding similar
results for the star parameters and a large disk inner radius (\( \approx 10^7 \) cm).
than zero, and the neutron star emission may also be partially beamed; this value is smaller than the one estimated by Burderi et al. 2003, since they did not account for the contamination from nearby stars). The required magnetic field is well in the range inferred from X-ray observations during the outbursts (see above). Prospects for directly observing SAX J1808.4–3658 pulsing in the X-ray band are rather hard since with XMM-Newton we collected less than 300 counts in 30 ks (Campana et al. 2002). Given the crowding around SAX J1808.4–3658 in the optical band, it would be difficult to detect an Hα nebula like that around PSR B1957+20. On the other hand, looking for a millisecond radio pulsar in the radio band would require searches at high frequencies to overcome the effects of free-free absorption (Campana et al. 1998a; Ergma & Antipova 1999; Burgay et al. 2003; Burderi et al. 2003) and a favorable orientation of the radio beam.

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