A 106 DAY PERIOD IN THE NUCLEAR SOURCE X-8 IN M33

Guillaume Dubus\(^1\) and Philip A. Charles
University of Oxford, Department of Astrophysics, Keble Road, Oxford OX1 3RH, England, UK

Knox S. Long
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218

and

Pasi J. Hakala
Mullard Space Science Laboratory, Holmbury St. Mary, Dorking, Surrey RH5 6NT, England, UK

Received 1997 July 21; accepted 1997 September 30; published 1997 October 23

ABSTRACT

With an X-ray luminosity of about \(10^{39}\) ergs s\(^{-1}\), the source X-8, coincident with the optical center of M33, is the most luminous X-ray source in the Local Group. However, its nature remains a mystery.

We present here new and archival \(\text{ROSAT}\) observations of X-8 spread over 6 yr that show variability and a periodicity of \(\sim 106\) days. This implies that (most of) the emission from M33 X-8 arises from a single object, perhaps a binary system with a black hole primary of \(\sim 10 M_{\odot}\). We suggest that the companion is a giant orbiting with a period of \(\sim 10\) days and that the observed modulation is “superorbital,” analogous to that seen in Cyg X-2 and X1820-30.

Subject headings: galaxies: individual (M33) — galaxies: nuclei — Local Group — X-rays: stars

1. INTRODUCTION

The nearby spiral galaxy M33 was first detected in X-rays using the \(\text{Einstein Observatory}\) Imaging Proportional Counter (IPC; Long et al. 1981) and the High Resolution Imager (HRI; Markert & Rallis 1983; Trinchieri, Fabbiano, & Peres 1988). These observations revealed a bright source, X-8, coincident with M33’s faint optical nucleus. The source comprised almost 70% of the total X-ray luminosity of M33. At M33’s distance, 795 kpc (van den Bergh 1991), X-8 has a \((0.15\pm4.5\) keV) \(L_X\) of \(\sim 10^{39}\) ergs\(^{-1}\) and is the brightest source in the Local Group.

Other observations of X-8 have been made using \(\text{EXOSAT}\) (Gottwald, Pietsch, & Hasinger 1987), \(\text{ASCA}\) (Takano et al. 1994), and the \(\text{ROSAT}\) Position Sensitive Proportional Counter (PSPC, Long et al. 1996) and HRI (Schulman & Bregman 1995). However, the nature of this source is still unresolved. Possibilities include a quiescent mini–active galactic nucleus (AGN; Trinchieri et al. 1988; Peres et al. 1989), a collection of X-ray binaries (Hernquist, Hut, & Kormendy 1991 hereafter HHK), and a new type of X-ray binary (Gottwald et al. 1991).

The temporal properties of X-8 are likely to be crucial to unraveling the problem. However, not much is known other than that the source has been persistent at about the same luminosity over a 15 yr baseline. Markert & Rallis (1983) did find (from \(\text{Einstein}\) HRI data) that the flux from X-8 had decreased by 40% on a timescale of 6 months, but similar variations were not detected in nearly simultaneous IPC and MPC observations. As a result, Peres et al. (1989) argued that the variability only affected energies below 1.2 keV. To address this problem, we have conducted a new study of the X-ray variability of X-8 based on \(\text{ROSAT}\) PSPC and HRI observations made between 1991 July and 1997 January. Our results concerning the other bright sources will be published elsewhere.

\(^1\) Present address: DARC, UPR 176 du CNRS, Observatoire de Paris Meudon, 5 place Janssen, 92195 Meudon, France.
We also tested the corrected mean fluxes for variability using fluxes. The photon arrival times were tested for variability using the Kolmogorov-Smirnov (KS) and the Cramer-Smirnov-von Mises (CSM) tests. We searched for power at frequencies between $10^{-3}$ and 10 Hz using a modified Fourier spectrum (Dubus et al. 1998) and for variability timescales following Collura et al. (1987). On corrected mean fluxes, we applied the standard $\chi^2$ test and the Lomb-Scargle (LS) normalized periodogram. We also tested the corrected mean fluxes for variability using the method of Maccacaro et al. (1987).

The analyses were applied independently to each observation and to various combined data sets: rh8 combines rh83 to rh60a (taken over 2 contiguous weeks), cen-h combines all centered (offset) HRI observations, hri has all the HRI data, and cen-p contains all centered PSPC observations. The data were combined both as mean orbital fluxes and observation averages, except for rh8, where only orbital means were combined. We did not attempt to include the 10 ks off-centered PSPC data into a single set or to combine HRI and PSPC data. Tests on (uncorrected) arrival times were not applied to data combining on- and off-centered data.

Within single orbits, the KS and CSM unbinned tests indicated time variability in three of the PSPC observations. Further analysis using the technique described by Dubus et al. (1998) revealed significant power at period of about 400 s. Thus, the short-term variability that we observed is due to the 400 s “wobble” used during ROSAT observations to reduce spatial variations in the detector response. As might be expected, in observation rp23c, when the amount of “wobble” was reduced, there was no significant power at 400 s. Averaging the flux on spacecraft orbits eliminates this effect. Significant peaks were not found in power spectra of the on-axis HRI data, with an upper limit of 20% (15% with the on-axis PSPC data) on any sinusoidal modulation at these frequencies (Dubus et al. 1998). Hence, the ROSAT data did not reveal any short-term variability in X-8.

Within individual observations, X-8 is also fairly constant.

The only exceptions were for rp23c, when the flux increased by $\approx 10\%$ in a few hours, and for rh11a, when the flux may have decreased by $\approx 10\%$ within a few days. The variations in count rate in rp23c were seen both in the soft (<0.84 keV) and hard (>0.84 keV) bands. This was also true if the boundary between soft and hard was set at 1.2 keV.

X-8 does appear to be variable in rh8 (which combines rh83-rh60a). This is the best sampled time interval with an exposure time 163 ks over 2 weeks (Fig. 1). We believe that the erratic behavior of X-8 during this time interval (Fig. 1) is real because of the following: (1) The on-axis observation is consistent with this hypothesis. (2) The background represents at most 10% of the raw flux, while there are $\approx 20\%$ variations. (3) Removing observations rh85 and rh87 (the farthest off-axis) or (4) changing the extraction regions has no effect. And (5), no similar variations were observed either in the background or in any other bright source in the field of view.

When observations over long time intervals ($\approx 1$ week) are considered, variability becomes far more obvious. As shown in Figure 2, X-8 varies by $\approx 20\%$ on a timescales of months. There are no reports of changes in the instrument sensitivity that could explain such variations.

| Observation | Offset (arcmin) | Dates | Duration (ks) |
|-------------|----------------|-------|---------------|
| rh20a       | 1              | 1992 Jan 8–12 | 19.1          |
| rh20b       | 1              | 1992 Aug 1–3  | 15.8          |
| rh83        | 14             | 1994 Aug 6–9  | 25.9          |
| rh84        | 13             | 1994 Aug 8–9  | 18.7          |
| rh85        | 16             | 1994 Aug 6–8  | 17.1          |
| rh86        | 7              | 1994 Aug 1–11 | 16.4          |
| rh87        | 17             | 1994 Jul 27–Aug 7 | 30.5 |
| rh60a       | 0              | 1994 Aug 10–11 | 8.0           |
| rh60b       | 0              | 1995 Jul 10–16 | 40.9          |
| rh11n       | 0              | 1996 Jan 18–Feb 8 | 46.4 |
| rh11a       | 0              | 1996 Jul 17–27 | 44.6          |
| rh03        | 0              | 1997 Jan 10–14 | 33.9          |

* The observation names correspond to the last digits of the ROSAT sequence numbers.
The PSPC data are included by assuming that the mean fluxes from the temporally close (within 10 days, see Table 1) observations rp232 and rh20b were the same and renormalized accordingly. PSPC and HRI data were not grouped together for analysis.

When LS analysis is carried out on the long data sets, a 106 day period is found with very high confidence in the HRI data. The LS analysis was confirmed with other methods contained in the STARLINK PERIOD package: CLEAN, $\chi^2$ fit to a sine wave, and phase dispersion minimization (PDM) methods. All yield a period of 105.9 ± 0.1 days. The data folded on the 106 day period are shown in Figure 3. With this period, the erratic behavior in data set rh8 can be associated with the rise time at phases 0.8–1.0. The folded renormalized PSPC data fits in very well, although it does not separately reveal a 106 day periodicity, at least in part because there are so few PSPC observations.

The period is also found in the centered observations alone, whether background-corrected or not, and so it is not an artifact of the corrections and/or pointings. Removing each observation in turn to see if the detection is due to one in particular, we find a peak of either ~52 or 105.9 days whenever there is a sufficient time base. The alias at ~52 days is ruled out by the last HRI observation, rh3 (obtained at phase 0.40–0.45; Fig. 3). The associated background showed no structure when folded on the 106 day period, and exhibits no variation greater than 10% of the amplitude of the X-8 modulation.

Simulating the X-8 data with a constant Poisson flux at the same mean gave no significant peaks in the LS analysis. Also, colored noise is unlikely at such low frequencies. While active galactic nuclei have a red noise power spectrum above $\sim 10^{-5}$ Hz, white noise dominates below that (McHardy 1988). The robustness to different changes in the data, the amplitude of the signal, the good phase coverage, and the fit of the PSPC data all testify in favor of the reality of this periodic behavior.

For completeness, Figure 3 also contains the folded mean fluxes of the three *Einstein* HRI and two IPC observations given by Peres et al. (1989). (Details of the cross calibration between the *Einstein* HRI and IPC can be also be found there.) Our renormalization to the *ROSAT* HRI count rate is arbitrary. Despite the normalization uncertainties, the *Einstein* HRI data appear consistent with the 106 day period. One of the IPC points may be discrepant, but with only two measurements, this discrepancy could easily be due to the difficulties associated with normalization. There were simply not enough *Einstein* observations to obtain a robust result.

### 4. DISCUSSION

Although X-8 is the brightest X-ray source in the Local Group, the nucleus of M33 is optically inconspicuous and semistellar (Kormendy & McClure 1993, hereafter KM), with a core radius of $\leq 0.3$ pc and a low-velocity dispersion of about 21 km s$^{-1}$. This implies a central relaxation time of $\sim 10^5$ yr. Thus, it is likely that the nucleus has undergone core collapse. HHK suggested that the M33 nucleus resembles a globular cluster and that the intense X-ray emission is due to $\sim 10$ low-mass X-ray binaries (LMXBs) formed during the core collapse, each with a luminosity of $\sim 10^{38}$ ergs$^{-1}$. (As noted by HHK, this requires sources brighter by a factor of 10 than galactic globular cluster LMXB sources.)

A 106 day period renders this scenario unlikely. A 10% amplitude for the X-8 periodic variations requires that one of the 10 objects modulates its luminosity by almost 100%, i.e., that it is transient. But this poses several problems: (1) this would be by far the shortest known transient recurrence time; (2) the quiescence interval would be extremely short; and (3) the outburst regularity would be exceptional. X-ray transients such as the neutron star LMXB Aql X-1 or the black hole candidate 4U 1630–47 show outbursts on timescales of a few hundred days but are not periodic (Kuulkers et al. 1997). The detection of the 106 day period over ~20 cycles implies a regularity and a short duty cycle incompatible with typical soft X-ray transients. We conclude that most of the X-8 luminosity arises from a single object.

One possibility is that the M33 nucleus contains a quiescent AGN. However, KM’s upper limit of $10^9 M_{\odot}$ on the mass contained in the inner 0.3 pc of M33 rules out the presence of a supermassive black hole and makes the interpretation of X-8 as a quiescent AGN untenable. This conclusion is further supported by the ASCA (Takano et al. 1994) and EXOSAT (Gottwald et al. 1987) X-ray spectra of X-8, which are best described by a power law plus an exponential cutoff above 2 keV, unlike known AGNs.

On the other hand, core collapse could have lead to the formation of a stellar mass black hole (KM, with $L_X \sim 10^{38}$ ergs$^{-1}$, corresponding to an Eddington-limited 10 $M_{\odot}$ black hole accreting at $M \sim 10^{-7} M_{\odot}$ yr$^{-1}$). The X-8 spectrum is softer than typical neutron star LMXBs, but comparable to LMXB black hole candidate spectra (Takano et al. 1994).

In principle, the mass transfer could arise from the wind of a massive O-B star. But such stars are not expected in the globular cluster–like nucleus of M33 and hence are excluded. Alternatively, tidal capture in the core could form a system in which the companion is degenerate. In this case, $M$ implies
$P_{\text{orb}} \sim 0.1 \text{ hr}$, and the mass of the donor star would be $\sim 0.1 M_\odot$ (King 1988), similar to the globular cluster source X1820–30. This neutron star LMXB has a “superorbital” variation of $\sim 20\%$ and 176 days, the origin of which is unknown. However, as the timescale for angular momentum losses through gravitational radiation is close to $10^4 \text{ yr} (\sim 10^6 \text{ yr for X1820–30})$, it is unlikely that we are observing a degenerate system in X-8.

A 106 day orbital period would be compatible with an evolved companion with a 0.3 $M_\odot$ helium core and a total mass of $\sim 2 M_\odot$ (King et al. 1997a). This would make it the longest known orbital period in an X-ray binary. But King et al. (1997a, 1997b) have shown that such systems would certainly be transient, and this is not observed here. To make the source persistent, one is led to orbital periods of $\sim 10$ days and inconsistent mass ratios close to unity.

The assumptions of King et al. (1997a, 1997b) do not hold if the companion is massive enough. For instance, the transient GRO J1655–40 is a 7 $M_\odot$ black hole binary with a 2.3 $M_\odot$ companion and $M \sim 10^{-7} M_\odot \text{ yr}^{-1}$ (Orosz & Bailyn 1997). The companion is probably crossing the Hertzsprung gap, evolving to the giant branch, and this places GRO J1655–40 in a narrow transient strip in an otherwise persistent luminosity domain (Kolb et al. 1997). Following Figure 2 of Kolb et al. (1997), it is thus conceivable to have a persistent source such as X-8 if the companion is a $\geq 2.5 M_\odot$ giant with $P_{\text{orb}} \leq 10$ days. We note that O’Connell (1983) found evidence in the nucleus of M33 for an increased population of intermediate mass ($2-5 M_\odot$) stars as compared with the M31 nucleus or our Galaxy.

The origin of the 106 day period is still a problem. Precession of a warped disk (Maloney, Begelman, & Pringle 1996) would lead to eclipses rather than a modulation. King et al. (1997a) used the van Paradijs (1996) criterion for instability, i.e., that a necessary condition for instability is that the disk temperature be somewhere in the disk below the hydrogen ionization temperature of 6500 K. This condition for stability is most stringent at the outer radius, where the temperature is lowest. Irradiation of the disk by the central X-ray source can have a major influence on this temperature (King et al. 1997a). With a giant companion of $\sim 2.5 M_\odot$ and $P_{\text{orb}} \sim 10$ days, the outer disk radius would be much larger than in most binary systems, and irradiation could be limited only to the inner parts of the accretion disk. Relaxing the van Paradijs criterion could allow instabilities to exist in the outer regions, leading to variability in the source and possibly “superorbital” modulation. This will be the subject of a future paper.

We thank Jean-Pierre Lasota, Jean-Marie Hameury, Andrew King, and Erik Kuulkers for fruitful discussions on various parts of this work. We acknowledge support from the British-French joint research program Alliance and from NASA grant NAG 5-1539 to the STScI. This research has made use of data obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA-Goddard Space Flight Center.

\section*{REFERENCES}

Collura, A., Maggio, A., Sciortino, S., Serio, S., Vaiana, G. S., & Rosner, R. 1987, ApJ, 315, 340

David, L. P., Harnden, F. R., Jr., Kearns, K. E., & Zombeck, M. V. 1996, The ROSAT HRI Calibration Report. U.S. ROSAT Science Data Center (Washington: Smithsonian Astrophys. Obs.)

Dubus, G., Charles, P. A., Long, K. S., Hakala, P. J., & Kuulkers, E. 1998, in preparation

Gottwald, M., Pietsch, W., & Hasinger, G. 1987, A&A, 175, 45

Hernquist, L., Hut, P., & Kormendy, J. 1991, Nature, 354, 376

King, A. R. 1988, QJRAS, 29, 1

King, A. R., Frank, J., Kolb, U., & Ritter, H. 1997a, ApJ, 484, 844

Kolb, U., King, A. R., Ritter, H., & Frank, J. 1997, ApJ, 485, L33

Kormendy, J., & McClure, R. D. 1993, AJ, 105, 1793

Kuulkers, E., Parmar, A. N., Kitamoto, S., Cominsky, L. R., & Sood, R. K. 1997, MNRAS, in press

Long, K. S., Charles, P. A., Blair, W. P., & Gordon, S. M. 1996, ApJ, 466, 750

Long, K. S., D’Odorico, S., Charles, P. A., & Dopita, M. A. 1981, ApJ, 246, L61

Maccarato, T., Garilli, B., & Mereghetti, S. 1987, AJ, 93, 1484

Maloney, P. R., Begelman, M. C., & Pringle, J. E. 1996, ApJ, 472, 582

Markert, T. H., & Rallis, A. D. 1983, ApJ, 275, 571

McHardy, I. 1988, X-Ray Astronomy with EXOSAT, ed. R. Pallavicini & N. White (Mem. Soc. Astron. Italiana Vol. 59), 239

O’Connell, R. W. 1983, ApJ, 267, 80

Orosz, J. A., & Bailyn, C. D. 1997, ApJ, 477, 876

Peres, G., Reale, F., Collura, A., & Fabbiani, G. 1989, ApJ, 336, 140

Schulman, E., & Bregman, J. N. 1995, ApJ, 441, 568

Takano, M., Mitsuda, K., Fukazawa, Y., & Nagase, F. 1994, ApJ, 436, L47

Trinchieri, G., Fabbiani, G., & Peres, G. 1988, ApJ, 325, 531

Trümper, J. 1984, Phys. Scripta, T7, 209

van den Bergh, S. 1991, PASP 103, 609

van Paradijs, J. 1996, ApJ, 464, L139