THE ASTROPHYSICAL JOURNAL, 420:L63–L66, 1994 January 10

TWO VERY LUMINOUS VARIABLE X-RAY SOURCES IN M82

A. COLLURA
Istituto per le Applicazioni Interdisciplinari della Fisica-CNR, Via Archirafi 36, Palermo, Italy
FABIO REALE
Istituto ed Osservatorio Astronomico, Piazza del Parlamento 1, I-90134 Palermo, Italy
AND
ERIC SCHULMAN AND JOEL N. BREGMAN
Department of Astronomy, University of Michigan, Ann Arbor, MI 48109-1090
Received 1993 August 23; accepted 1993 October 26

ABSTRACT

We report on a variability study of X-ray sources in the starburst galaxy M82, based on *ROSAT* and *Einstein* High-Resolution Imager observations. In particular, we concentrate our analysis on two bright sources which exhibit significant variability. The brightest source in M82 is located in the central core of the galaxy, is variable within individual *ROSAT* observations, and indication are that it might have varied between the *Einstein* and the *ROSAT* observations. It is the most luminous X-ray binary candidate yet known. The other source is located outside the crowded central region and was very bright in the *Einstein* observation, but was not detected by *ROSAT*, despite the larger effective area of the instrument and the much longer exposure. The detection of variability poses strong constraints on the X-ray luminosity of individual components of the X-ray sources. Even if both sources are radiating at the Eddington limit, their mass would be at least several $M_{\odot}$, making them candidates for extragalactic black holes.

Subject headings: binaries: eclipsing — galaxies: individual (M82) — X-rays: galaxies

1. INTRODUCTION

M82 is a virtually unexcelled astrophysical laboratory of high-energy events made readily observable because the galaxy is relatively close to our own (a distance of 3.25 Mpc to M82 has been assumed throughout this work). A burst of star formation, probably triggered 10^7–10^8 years ago by a strong tidal interaction with M81, makes M82 very different from other nearby galaxies, and provides a unique opportunity for the study of a variety of phenomena. In particular, the X-ray emission of M82 is characterized—among other features that will be discussed elsewhere (Bregman, Schulman, & Tomisaka 1994)—by the presence of strong, pointlike sources, whose X-ray luminosity, if arising from a single object, is much higher than previously observed from objects other than active galactic nuclei (AGNs). Such very luminous X-ray sources, first detected in M82 by *Einstein* (Watson, Stanger, & Griffiths 1984), studied in radio by Wilkinson & De Bruyn (1984), and again observed and detected by *EXOSAT* (Schaaf et al. 1989), have been proposed as black hole candidates by Stocke, Wurtz, & Kuhr (1991), since the sources are radiating at far above the Eddington limit for a solar mass object.

In this *Letter* we report on the detection of variability of the X-ray emission from two of these sources. Since the emission observed from sources appearing pointlike at a few arcsec resolution might actually be due to a multiplicity of distinct sources, the study of variability may be crucial in constraining the contribution of individual sources to the observed emission. In addition, the shape and timescale of the light curves of the variable sources might give further hints on the nature of the sources, suggesting possible interpretations for the physical mechanisms underlying the X-ray emission.

2. DATA AND ANALYSIS

This work is based mainly on two observations obtained with the *ROSAT* High-resolution Imager (HRI), sensitive in the 0.1–2.5 keV band, but takes advantage also of previous observations. In particular, we have analyzed an observation taken with the *Einstein* High-Resolution Imager (cf. Watson et al. 1984), and have also considered *EXOSAT* results reported in the literature (Schaaf et al. 1989). Table 1 reports, for each *Einstein* and *ROSAT* observation, the start and stop time, the observing instrument, and the effective exposure time. Each observation consists of several good time intervals (GTI), separated by data gaps. The *ROSAT* observation RH 600021a, performed in 1991, has a very long gap (3.147×10^6 s) between the first ≈ 170 s and the rest of the observation. The contour plot images of the *Einstein* and *ROSAT* HRI observations are shown in Figures 1*a* and 1*b*, respectively, in which the crosses and numbers indicate the two sources studied in this work. In Table 2 we report the X-ray coordinates of the sources as obtained from the *Einstein* and *ROSAT* HRI observations.

The source cells used for the variability analysis and for the derivation of fluxes were circular cells with 10″ radius, centered on the maximum likelihood position for the source corresponding to the local peak of intensity, according to standard detection processing. The variability was studied over pulse height channels 2–10, in order to improve UV and noise rejection. The *ROSAT* and *Einstein* positions of source 2 coincide within the uncertainty in the aspect solution, and since source 1 was not detected by *ROSAT*, the counts detected in the cell centered on the Einstein position were used to provide an upper limit to its X-ray flux in the *ROSAT* observation. In order to study variability within individual observations we

TABLE 1

Einstein and *ROSAT* High-Resolution Imager Observations of M82

Sequence Number	Start Day	Start Time	Stop Day	Stop Time	On-Time
EH 586	1979 May 03	$19^h00^m27^s$	1979 May 06	$18^h03^m43^s$	13110.7
RH 60021a	1991 Mar 25	05 15 34	1991 May 04	23 36 31	24613.0
RH 60021b	1992 Oct 20	14 14 58	1992 Oct 26	23 40 07	9496.0

have applied three different tests: the Kolmogorov-Smirnov test and the Cramer-Smirnov-Von Mises test (Eadie et al. 1971), which compare the cumulative distribution of photon arrival times with the distribution expected from a constant source, and a modified χ^2 test able to provide results independent of the chosen binning (Collura et al. 1987). In addition, we have checked variability between different parts of each observation separated by long time gaps comparing the count rates as described in Maccacaro, Garilli, & Mereghetti (1987).

We have also compared the fluxes obtained from *Einstein* and *ROSAT* observations, according to spectral models with KT = 1–3 keV and log N_h = 21.0–21.5, applying the appropriate scattering correction, and subtracting a locally estimated background. We note that the background is dominated by the diffuse emission of the galaxy, and is highly nonuniform; it constitutes the largest source of uncertainty in the flux determination. The evaluation of the statistical significance of results obtained by comparing the *Einstein* and *ROSAT* fluxes is not straightforward, given the possible cross-calibration errors and the large uncertainty due to the background evaluation. We have therefore refrained from stating the significance of the flux variations, and simply report the flux estimates in the next section, where we also discuss how these estimates are influenced by the choice of the spectral model. For source 1 we also provide a rough but conservative estimate of the significance of its variation between the *Einstein* and *ROSAT* observations.

3. RESULTS

3.1. *Variability within Individual Observations*

Neither of the two sources showed significant variability inside the *Einstein* observation, source 1, was not detected by *ROSAT*, and source 2 showed variability inside the second *ROSAT* observation. The three tests applied give a probability of $\lesssim 10^{-5}$ that the detected variability of source 2 arises from chance fluctuations of a constant source. The *ROSAT* light curve of source 2 (pulse height channels 2–10), shown in Figure 2, reports the count rate derived in the source cell without subtracting any background contribution, which may be estimated at about 0.016 counts s^{-1}. During the second *ROSAT* observation, RH 600021b, the count rate including background decreased throughout the observation, eventually reaching $\approx 50\%$ of its initial value, although the long gaps do not allow us to ascertain whether it was a monotonic decrease or not. The background was checked in several regions to rule out spurious variability due to background fluctuations, and we also studied the background behavior in an annular region contiguous to the source cell and centered on the source. If the source variability were due to pointing instability, fluctuations in the collection of source photons would reflect in background fluctuations anticorrelated with source variability. Such an effect has not been observed. We also tried a 20″ radius cell for collecting the source photons and the source remained significantly variable (> 3 σ) despite the larger background contribution.

3.2. *Variability between Einstein and ROSAT Observations*

The variability between *Einstein* and *ROSAT* is more difficult to study, because of cross-calibration uncertainties and of the different passbands of the two instruments, which require assumptions on the spectrum of the sources. Furthermore, there are large uncertainties in the determination of the background contribution to the source total count rate, because of the presence of a significant and nonuniform diffuse emission around the galactic center.

Source 1, which had been detected at a significance level of more than 5 σ by *Einstein* (Watson et al. 1984), was not detected by *ROSAT* despite the much higher sensitivity of the observations. Assuming a thermal spectrum with KT = 3 keV and log N_H = 21.0, and taking the background level of the *ROSAT* observations to be 0.06 counts pixel^{-1} and the background level of the *Einstein* observations to be 0.01 counts pixel^{-1}, the 3 σ upper limit derived from the *ROSAT* observation indicates that the luminosity of source 1 decreased by a factor of ≥ 17 (by a factor of more than 13 if one assumes KT = 1 keV). If we assume that source 2 was half as intense during the *Einstein* observation as during the *ROSAT* observation (see below), we can derive a conversion factor between the count rates of the two instruments. A conservative estimate of the significance level of the variation between the *Einstein* count rate of source 1 and the *ROSAT* upper limit of source 1 is well above the 5 σ level.

Toward source 2 the extinction is substantial, probably near 2–3 × 10^{21} cm^{-2}. For log N_H = 21.5, a thermal Raymond-Smith model with KT = 3 keV and cosmic abundances, and a background level of 0.45 counts pixel^{-1} (there is much diffuse emission because the source is very close to the galactic center), the time-averaged *ROSAT* HRI luminosity is L_X(0.1–2.5 keV) = 6.3 × 10^{39} ergs s^{-1}, or 1.8 times brighter than the luminosity in the same band determined with the *Einstein* HRI using a background level of 0.05 counts pixel^{-1}. For the same model but with a temperature of 1 keV, the *ROSAT* HRI luminosity is L_X(0.1–2.5 keV) = 5.0 × 10^{39} ergs s^{-1}, or 1.5 times brighter than the flux from *Einstein*. For a lower absorption column, such as log N_H = 21.3 (and for KT = 3 keV), the object is 2.0 times brighter in the *ROSAT* than in the *Einstein* observation. For any possible spectral model, the source

TABLE 2

Einstein and *ROSAT* High-Resolution Imager Coordinates of Source 1 and Source 2

Source	Year	α(*Einstein*)	δ(*Einstein*)	α(*ROSAT*)	δ(*ROSAT*)
1	1950	$9^h51^m41^s.5$	69°54′58″.4	...	...
	2000	9 55 40.8	69 40 53.9	...	...
2	1950	9 51 31.9	69 55 07.6	...	...
	2000	9 55 50.3	69 40 44.4	$9^h55^m50^s.4$	69°40′47″.5

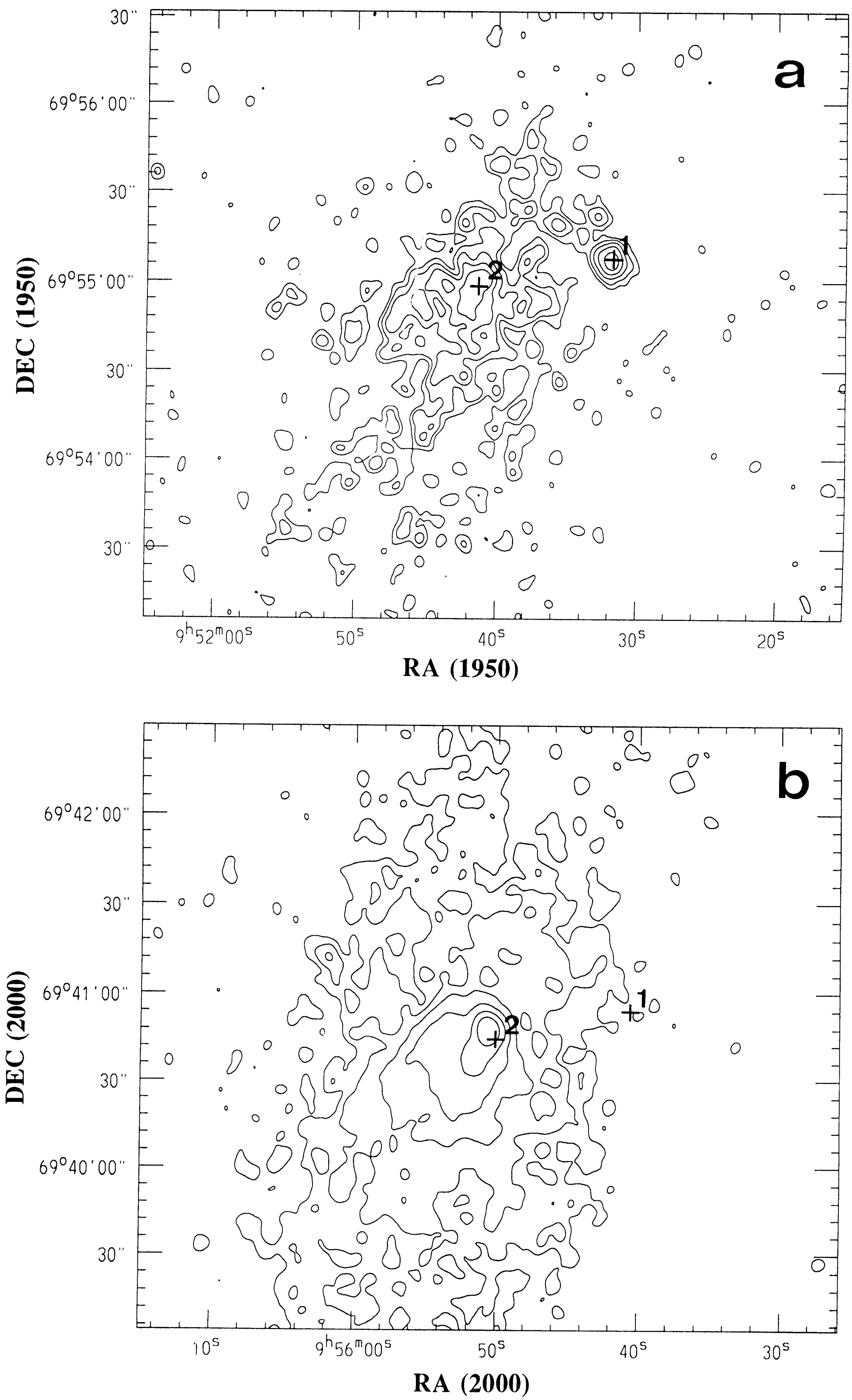

FIG. 1.—Contour map of the X-ray emission from the M82 core region as observed by the *Einstein* HRI (*a*) and by the *ROSAT* HRI (*b*) (cf. Table 1). Five and six logarithmically spaced contours normalized to the maximum flux value are reported respectively in (*a*) and (*b*). The lowest levels are 10% and 1% of the maximum, respectively. The positions of sources 1 and 2 (cf. Table 2) as obtained from the *Einstein* HRI are marked in both panels.

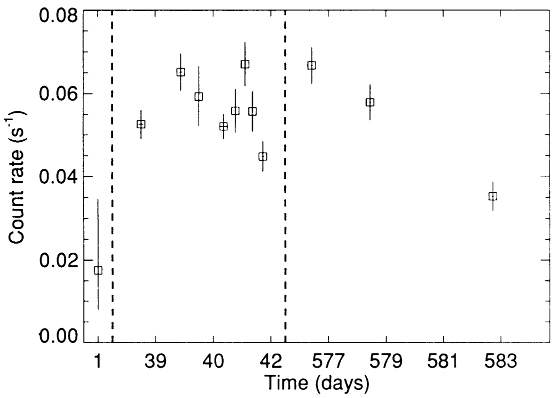

FIG. 2.—Light curve of source 2 observed by the *ROSAT* HRI in a cell of 10″ radius (pulse height channels 2–10). The count rate is averaged over good time intervals separated by gaps not longer than 10,000 seconds. Horizontal error bars limit the time spans over which the count rate is averaged. The dashed lines mark very long gaps separating segments of continuous observations. The time (in days) is reckoned since 1 day before the first (very short) piece of the first *ROSAT* observation.

observed by the *ROSAT* HRI is at least 1.5 as bright as it was when observed by the *Einstein* HRI. Given the uncertainties stated above, we are not able to make any firm statement about the statistical significance of the latter result, although it might suggest that during the *Einstein* observation the source was in a low state, as the one observed during the later part of the second *ROSAT* observation.

4. DISCUSSION

As pointed out by Stocke et al. (1991), source 1 is unlikely to be a transient source, since it was detected by *EXOSAT* 3 years later than its first detection, at approximately the same flux. Stocke et al. (1991) have performed a search for an optical counterpart down to $m_v = 23$ and found a blue object in the error circle of the source, at $m^v = 22$. The F_X/F_v ratios computed both assuming that the detected blue object is the optical counterpart of source 1 and that it is not, are compatible only with the hypothesis that source 1 is a compact X-ray binary, or a combination of several compact X-ray binaries. The detection of variability with an amplitude of at least a factor of 10 or more is strong evidence that we are observing an individual X-ray source. Its X-ray luminosity of 1.4×10^{39} ergs s^{-1}, far above the Eddington limit for a Solar mass object, is suggestive of a massive compact object. One might wonder why it was not detected by either of the two *ROSAT* observations but given the relatively short time span of each *ROSAT* observation, and the behavior typical of massive X-ray binary systems, which often exhibit periodic eclipses and irregular light curves with low states unrelated to eclipses (Tananbaum & Tucker 1974), the nondetection can easily be reconciled with the X-ray binary hypothesis. Further observations, if able to detect the source, would definitely prove that it is still there, and could provide a better characterization of its variability, especially if periodic eclipses could be detected.

During *ROSAT* observation RH 600021b the luminosity of source 2 in the band 0.1–2.5 keV changed by 2.9×10^{39} ergs s^{-1}, assuming $KT = 3$ keV and log $N_H = 21.5$, as derived from the difference between high and low states in the light curve. This luminosity difference is not affected by the background estimates and can safely be ascribed to an individual source (lower states might have escaped detection), unless unlikely beatings between variability of different sources are postulated. If this value is assumed as a lower limit to the luminosity of an individual source, this luminosity corresponds to the Eddington luminosity—computed for pure electron scattering—of an object of $\sim 20\ M_\odot$. Therefore source 2 is a candidate for the most luminous X-ray binary yet known and for a black hole as well.

For the sake of completeness, although unlikely, we mention the possibility that this source could be a background active galactic nucleus that has been microlensed by the nuclear star cluster in M82.

We conclude that the high X-ray luminosities of these variable sources, suggestive of very high-mass compact objects, confirm the peculiarity of the zoo of X-ray sources in M82, and call for further observations of this galaxy.

We thank G. Peres and S. Serio for a critical reading of the text. We gratefully acknowledge support from NASA through NAGW-2135 and through NASA Graduate Student Research Program grant NGC-5090, from the Italian Ministero dell Universitá e Ricerca Scientifica e Tecnologica, and from the Agenzia Spaziale Italiana.

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