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ON THE NATURE OF THE X-RAY EMISSION FROM 1E 1024.0−5732/WACK 2134: THE FIRST X-RAY–SELECTED WOLF-RAYET STAR

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ABSTRACT

We report on a *ROSAT* PSPC observation of the X-ray source 1E 1024.0−5732. The optical identification with the emission-line star Wackerling 2134 is confirmed, but we do not find any evidence of the periodic pulsations at 61 ms which were previously reported in its X-ray flux. On the basis of the new timing and spectral results, a reexamination of the old X-ray and optical data, and a new optical spectrum, we propose that this source is a new Wolf-Rayet star of type WN6. The high level of X-ray emission hints at the presence of a binary companion to Wack 2134. This could be either an accreting compact object or a massive OB star, in which case the X-rays would be produced in the colliding winds of the two stars. The small equivalent widths of the Wolf-Rayet star emission lines strongly support the O-star companion hypothesis. If this scenario is confirmed, Wack 2134 would be the first case of an X-ray–selected Wolf-Rayet star.

Subject headings: binaries: close — stars: individual (1E 1024.0−5732) — stars: Wolf-Rayet — X-rays: stars

1. INTRODUCTION

The source 1E 1024.0−5732 was discovered with the *Einstein Observatory* during a search for soft X-ray counterparts of unidentified *COS B* γ-ray sources (Goldwurm, Caraveo, & Bignami 1987). These authors identified 1E 1024.0−5732 with the early-type, emission-line star Wackerling 2134, and reported a periodicity of 61 ms in its X-ray flux (Caraveo, Bignami & Goldwurm 1989, hereafter CBG). On the basis of the high X-ray–to–optical flux ratio, the presence of pulsations, and evidence of long-term variability between two X-ray observations, this source was interpreted as a rapidly spinning neutron star accreting matter from a massive companion. The 61 ms period reported by CBG, if confirmed, would be the shortest ever observed in an accreting X-ray pulsar and would have interesting implications for the modeling of the interaction between the accreting matter flow and the rotating magnetosphere of the neutron star (see, e.g., Stella, White, & Rosner 1986).

Here we report on a *ROSAT* observation of 1E 1024.0−5732 and propose a different scenario for the interpretation of this source.

2. DATA ANALYSIS AND RESULTS

2.1. *X-Ray Data*

1E 1024.0−5732 was observed with the *ROSAT* Position Sensitive Proportional Counter (PSPC) instrument between 1992 July 29 01:12 UT and July 30 9:36 UT, for a total net exposure time of 8990 s. For a description of the *ROSAT* mission and of the PSPC detector, see Trümper (1983) and Pfeffermann et al. (1986), respectively. The data analysis was performed using the EXSAS system (Zimmermann et al. 1993).

The three X-ray sources discovered by Goldwurm et al. (1987) are clearly detected in our observation, which in addition shows several fainter sources as well as diffuse emission (a detailed analysis on these objects will be reported in a future paper). 1E 1024.0−5732 is clearly detected with a net count rate in the 0.1–2.4 keV band of 0.0756 ± 0.003 counts $\mathrm{s^{-1}}$. Its position, determined with a maximum likelihood technique (Cruddace, Hasinger, & Schmitt 1988), is $\alpha(2000) = 10^{\mathrm{h}}25^{\mathrm{m}}56^{\mathrm{s}}.49$, $\delta(2000) = -57^\circ48'44''.4$ with a 90% confidence error radius of $3''.5$. This position has been corrected for residual systematic effects by means of a maximum likelihood cross-correlation between the pointlike sources detected in the inner region of the PSPC field of view (radius 20′) and the entries of the *Hubble Space Telescope* Guide Star Catalog (GSC). After the correction, nine sources (including 1E 1024.0−5732) could be identified with GSC stars.

To perform a spectral analysis of 1E 1024.0−5732 we selected all the counts (796) in a circle of radius 2′ centered on the source position. The background contribution has been estimated from a rectangular region at some distance from the source. The background subtracted spectrum has been rebinned in order to achieve a minimum of 5 σ statistics in each pulse height amplitude bin. A fit to a power-law model corrected by interstellar absorption gives a photon index $\Gamma = 1.6 \pm 1.6$ and an equivalent column density $N_{\mathrm{H}} = (9 \pm 6) \times 10^{21}$ $\mathrm{cm^{-2}}$. The best-fit χ^2 is 9.8 (for 7 d.o.f.). A thermal bremsstrahlung model gives an equally acceptable best fit for a temperature larger than 0.9 keV and $N_{\mathrm{H}} = (9 \pm 3) \times 10^{21}$ $\mathrm{cm^{-2}}$. The corresponding unabsorbed flux in the 1.0–2.4 keV band is between 2.8 and 4.3×10^{-12} ergs $\mathrm{cm^{-2}\ s^{-1}}$. The large errors on the spectral parameters arise from the fact that the source spectrum is highly absorbed, which makes it difficult to determine both the amount of interstellar absorption and the intrinsic parameters of the source spectrum.

The source is located in a region of slightly enhanced background caused by the diffuse X-ray emission probably associated with the nearby nebula RCW 49. We have therefore repeated the spectral analysis with different choices of the background regions, but due to the relatively high signal-to-noise ratio of 1E 1024.0−5732, the results do not change significantly.

The same counts extracted for the spectral fit of 1E 1024.0−5732 were used for the timing analysis, after correction of their time of arrivals to the solar system barycenter. We

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first looked for the 60.69 ms period by means of a Fourier analysis. The observation was divided into 37 intervals of 8192 bins each, with a bin size of 25 ms, and the resulting power spectra averaged together. No statistically significant peaks were present at 61 ms or elsewhere. Following van der Klis (1988) we can set a 90% upper limit of 29% on the rms of a pulsed source signal in the range 10–20 Hz. A search for periodicities in the same frequency range was also performed using a standard folding algorithm, but again no statistically significant signal was found. We looked for longer periodicities, up to the value of the satellite pointing wobbling (400 s), with negative results.

2.2. *Optical Data*

A single 600 s spectrum of Wack 2134 was obtained with the Cerro Tololo Inter-American Observatory (CTIO) 1.6 m telescope + GEC CCD + 158 lines mm^{-1} grating on the night of 1993 May 26. IRAF was used to reduce the spectrum, which is shown in Figure 2, and discussed in § 4.

3. COMPARISON WITH THE *Einstein* OBSERVATIONS

3.1. *Position and X-Ray Flux Results*

The *ROSAT* position for 1E 1024.0−5732 differs by less than 1″ from that of the star Wackerling 2134 and is compatible with the *Einstein* HRI error circle reported by CBG (radius 8″). No other optical objects are visible within or close to the ROSAT 3″.5 error circle. We thus confirm the identification of 1E 1024.0−5732 with the emission line star Wack 2134.

Assuming a thermal bremsstrahlung model, we have derived fluxes from the *Einstein* data varying the spectral parameters in the range determined with *ROSAT*. We then compared them with the *ROSAT* fluxes, looking for regions of compatibility in the parameter space. The conclusion is that, assuming the flux in the two observations to be the same, only the narrow range of parameters around $kT \sim 1$ keV and $N_H \sim 10^{22}$ cm^{-2} is consistent with both observations.

The level of coronal X-ray emission from stars is generally characterized in terms of the distance-independent ratio of X-ray to bolometric luminosity L_X/L_{bol}. On the basis of spectroscopic observations, CBG classified Wack 2134 as a star of spectral type O5 or earlier, and they derived an L_X/L_{bol} much larger than the average value of 10^{-7} observed in the first X-ray studies of O stars. Recently, all the *Einstein* observations of O-type stars have been reanalyzed in a systematic way by Chlebowski, Harnden, & Sciortino (1989) and Sciortino et al. (1990). Using the revised IPC count rate of 1E 1024.0−5732 extracted from the *Einstein* Database (0.054 ± 0.004 counts s^{-1}), we have recomputed the value of L_X/L_{bol}, applying exactly the same procedure followed by these authors: the X-ray luminosity, corrected for absorption, refers to the 0.2–3.5 keV energy range and is derived for a thermal spectrum with $kT = 0.5$ keV, the bolometric magnitude is given by $m_{\mathrm{bol}} = V + \mathrm{BC} - 3.1E(B-V)$. In Figure 1 the resulting values of L_X and L_{bol} are compared to those of all the O stars detected by Chlebowski et al. (1989). We have used $E(B-V) = 1.8$ (CBG), $V = 12.67$, and a distance of 3 kpc. The shaded area indicates the possible values for Wack 2134, obtained for the indicated N_H values and bolometric corrections in the range -4 to -3, appropriate for O-type stars (Humphreys & McElroy 1984). The strong dependence on the poorly constrained N_H value is evident. Though the L_X/L_{bol} ratio is higher than the average value for O stars, a coronal origin cannot be ruled out in the case of $N_H \leq 10^{22}$ cm^{-2}. Computing the 0.2–3.5 keV luminosity from the present *ROSAT* observation, one arrives at the same conclusion, although we note that our spectral analysis favors a temperature higher than that assumed for the computation of L_X/L_{bol} ($kT = 0.5$ keV).

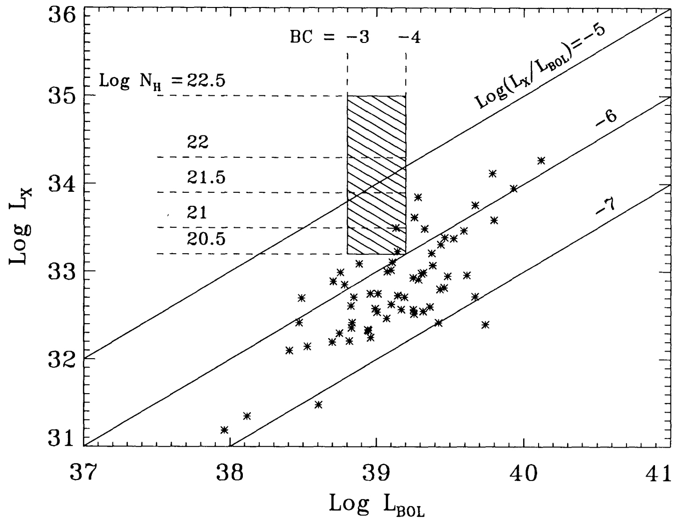

FIG. 1.—L_X vs. L_{bol} plot. The shaded box is the allowed region for 1E 1024.0−5732. The values for the interstellar absorption and bolometric correction are marked. The asterisks mark the position of the O stars in Chlebowski, Harnden, & Sciortino (1989).

3.2. *Timing Analysis Results*

The most important difference with respect to the observations reported by CBG is the lack of the 61 ms periodicity in our *ROSAT* data. A periodic signal such as that shown in Figure 2 of CBG (rms pulsed signal ∼44%) should have been easily detected in our observation, thanks to its better statistics (796 counts with respect to 337) and higher signal-to-noise ratio (24 with respect to ∼7). In the case of this highly absorbed source, the spectral responses of the *Einstein* IPC and *ROSAT* PSPC instruments are practically the same. Thus an energy dependence of the pulsed fraction cannot explain the lack of pulsations in our data. We believe that the statistical significance of the detection of the periodicity in the 1980 observation was overestimated by CBG, who did not take into account the number of periods searched in their fast Fourier analysis. A negative search for the same periodicity in the optical flux from Wack 2134 is reported by Dieters, Hill, & Watson (1990). We thus conclude that there is no evidence for the previously reported periodicity in 1E 1024.0−5732.

This is also supported by the following independent argument. Accretion onto a rotating magnetized object is possible only if the Keplerian velocity of the accreting matter at the magnetospheric radius is greater than the corresponding corotation velocity (see, e.g., Henrichs 1983). If this condition is not satisfied, the infalling matter, forced to corotate with the magnetic field, is subject to a centrifugal drag which prevents the accretion (Illarionov & Sunyaev 1975). Since the position of the magnetospheric radius depends on the mass accretion rate, the above condition yields a minimum luminosity at which accretion onto a neutron star is possible (Stella et al. 1986):

$$L_{\mathrm{min}} \sim 6 \times 10^{40} \left(\frac{B}{10^{12}\ \mathrm{G}}\right)^{2} \left(\frac{P}{0.06\ \mathrm{s}}\right)^{-7/3} \mathrm{ergs\ s^{-1}}\,,$$

where B is the neutron star magnetic field and P is its spin period. The observations show that this relation is satisfied by all the known accreting X-ray pulsars, including the fastest one (A0538−66; $P = 69$ ms). This transient source is located in the Large Magellanic Cloud, and, during the outburst in which the pulsations were detected, it reached a luminosity of the order of 10^{39} ergs s^{-1} (Skinner et al. 1982). An extreme choice of the spectral parameters could yield a luminosity of $\sim 6 \times 10^{34}$ $(d/1$ kpc$)^2$ ergs s^{-1} for 1E 1024.0−5732. But even in this case and for a distance of 10 kpc (which would place the source at the edge of our Galaxy), a magnetic field as low as 10^{10} G would be required, at variance with the typical values observed in high-mass X-ray binaries.

4. DISCUSSION

The results reported above do not exclude the possibility that the X-ray emission in 1E 1024.0−5732/Wack 2134 originates from accretion onto a neutron star in a massive binary system as proposed by CBG. However, due to the lack of pulsations and the dependence of $L_X/L_{\rm bol}$ on the poorly constrained interstellar absorption, there is no compelling evidence requiring the presence of an accreting compact object.

Here we propose an alternative scenario for this source, based on a new optical spectrum obtained at CTIO (Fig. 2). CBG already noted that some of the spectral features of Wack 2134 are reminiscent of those of Wolf-Rayet stars, but they preferred a classification in terms of a normal O-type star, whose atmosphere was possibly influenced by the presence of the X-ray–emitting neutron star. We note that the spectrum of Wack 2134 is remarkably similar to that of the new Wolf-Rayet star (WR 20a) recently discovered in the open cluster Westerlund 2 by Moffat, Shara, & Potter (1991). Both objects show emission lines of N IV 4058, N III 4640, He II 4686, C IV 5806, He I 5876, Hα, and Hβ, as well as strong interstellar absorption features and a heavily reddened continuum (cf. Fig. 4 of BCG with Fig. 7 of Shara et al. 1991). It is interesting to note that Wack 2134 lies only 16′ from the newly discovered star WR 20a. Two other new W-R stars were found by the same authors in the same sky region (WR 19a and WR 20b, within about 1°) and have spectra very similar to those of Wack 2134 and WR 20a, except for the presence of He II 5411 in emission. This line is absent in WR 20a, while it appears in absorption in the spectrum of Wack 2134. These three stars are classified as WN7 by Shara et al., thus suggesting a similar classification for Wack 2134.

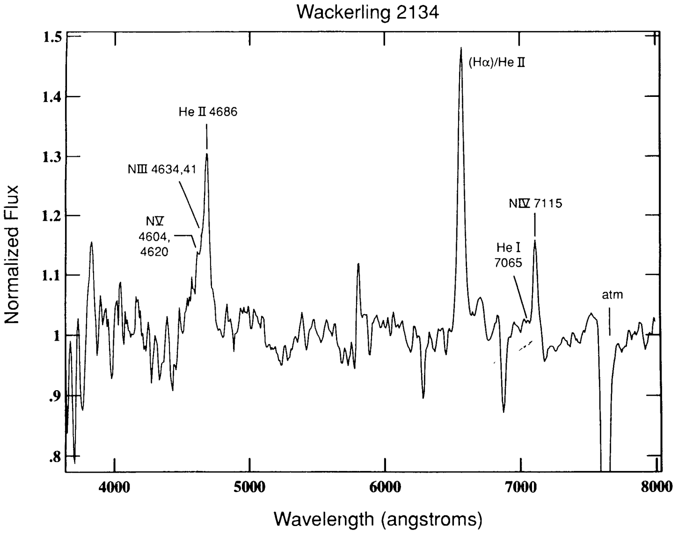

FIG. 2.—CTIO 1.6 m spectrum of Wack 2134 with continuum normalized to unit flux to more easily see the relevant emission lines.

A more detailed analysis, made possible by the near-IR spectral coverage of Figure 2, determines the W-R star subtype as WN6. Comparison with Figure 2*a* of Conti, Massey, & Vreux (1990) shows that Wack 2134, with N IV 7115 much stronger than He I 7065, must be of subtype WN6 or earlier. The presence of weak N V 4604,4620 supports subtype WN6 (though WN5 cannot be ruled out), and excludes subtypes WN4 or earlier. The FWHM of the He II/Hα emission line is 40 Å, corresponding to an expansion velocity of 1855 km s^{-1}. This is normal for a W-R star, but incompatible with the suggestion of CBG that Wack 2134 might be an O star. Perhaps most important of all are the equivalent widths of the emission lines: 17 Å for He II 4686, 24 Å for He II 6563, and 6 Å for N IV 7115. These are about 10 times weaker than the strongest lined (single) W-R stars, but comparable to those of known W-R + O binaries. This strongly suggests the presence of a luminous O-type companion.

In general, Wolf-Rayet stars have X-ray luminosities similar to those of normal O-type stars (or, possibly, even smaller), as indicated by a few tens of *Einstein* detections and upper limits, which yielded average values of $L_X/L_{\rm bol} \sim 10^{-7}$ (White, & Long 1986; Sanders et al. 1985; Seward & Chlebowski 1982). There are, however, a few notable exceptions of Wolf-Rayet stars with much higher X-ray luminosities, such as WR 140 (Pollock 1987) and WR 25 (Seward & Chlebowski 1982). The strong and variable X-ray luminosity of WR 140 is thought to originate in a shock which forms where the massive wind from the W-R stars collides with that of its O-star companion (Williams et al. 1990). These shocks, also responsible for nonthermal radio emission, are expected to form in all the W-Rs with massive OB-type companions (see, e.g., Myasnikov & Zhekov 1991; Stevens, Blondin, & Pollock 1992), but due to the absorption in the W-R winds, the resulting enhanced X-ray (and radio) emission is more evident in wide binaries, where the shock occurs outside the densest wind regions. An alternative explanation for the X-ray–bright W-R stars involves accretion onto a compact object. For example, White & Long (1986) proposed a white dwarf or black hole companion to explain the X-ray variability observed in HD 50896 (WR 6, EZ CMa). For a distance of the order of that derived by Shara et al. (1991) for WR 20a (4.5–6.3 kpc), the X-ray luminosity of Wack 2134 is 1×10^{34} $(d/5$ kpc$)^2$ ergs s^{-1}. This is comparable to that of the X-ray strongest W-R stars mentioned above, indicating that similar mechanisms might be at work in this source. The results of the *ROSAT* spectral fit, indicating a temperature consistent with a few keV, and the presence of an O-type companion suggested by the optical data, also favor this interpretation.

5. CONCLUSIONS

Independent of the spectral classification of Wack 2134, its level of X-ray emission is higher than that expected in the case of coronal emission from an early-type star, unless the absorption is smaller than several times 10^{21} cm^{-2}. This seems unlikely, given the low Galactic latitude and estimated distance, as well as the indications from both the *Einstein* and *ROSAT* spectral results. A compact object accreting from the wind of Wack 2134 remains a barely possible explanation for the excess X-ray flux, but the presence of a rapidly spinning neutron star finds no support in our *ROSAT* data, since we do not confirm the previously reported periodicity.

An interesting possibility is suggested by the optical characteristics of Wack 2134, very similar to those of other WN Wolf-Rayet stars recently discovered in the same region of sky (the Carina arm). Wack 2134 represents, to our knowledge, the first case of a Wolf-Rayet star discovered through its X-ray emission. Its higher than average $L_X/L_{\rm bol}$ is thus naturally explained as a typical result of the bias intrinsic in "X-ray–selected" samples. Further optical spectroscopy of Wack 2134 is clearly needed to confirm the proposed classification and especially to search for the presence of an O-type binary companion. The detection of nonthermal radio emission would favor the colliding wind binary scenario, as opposed to the accretion one.

1E 1024.0−5732/Wack 2134 lies in the error box of the *COS B* γ-ray source 2CG 284−00 (see Bignami & Hermsen 1983). A recently published model of colliding winds (Eichler & Usov 1993) predicts, under certain assumptions, a detectable level of γ-ray emission for the WC7/O4–5 binary WR 140. The application of this model to explain 2CG 284−00 would require even more extreme values of the parameters, due to the larger distance of Wack 2134 compared to that of WR 140 ($\sim$1 kpc). An association between Wack 2134 and 2CG 284−00 seems thus rather unlikely.

Wolf-Rayet stars are extremely rare objects; less than 200 are known in our Galaxy (van der Hucht 1992). Their study, besides the obvious interest in the context of stellar evolution and of the phenomena related to the exceptional mass loss in W-R stars, is relevant to the understanding of the star formation processes on the overall Galactic scale. In addition, being very luminous objects, they can be used to trace the Galactic structure out to large distances, and as powerful probes of the interstellar medium. These are the main motivations behind the extensive searches aimed at the discovery of new W-R stars, which, up to now, have been carried out mainly in the optical domain. X-ray observations might be an efficient way to discover new W-R candidates, possibly with characteristics different than those discovered in optical surveys. The theoretical models of colliding wind binaries predict X-ray luminosities higher than those observed in the majority of the W-R + OB stars (Myasnikov & Zhekov 1993; Stevens et al. 1992). It is possible that the presence of strong X-ray and radio emission affects the optical properties of these objects, making them more difficult to discover in the optical. In particular, the dilution of the W-R star emission lines by bright, O-type companions can hide such stars from emission-line surveys like that of Shara et al. (1991). On the other hand, such objects would be more easily discovered through X-ray searches, possibly correlated with radio observations. In this respect a great potential is offered by the *ROSAT* All Sky Survey, but also the less extensive surveys carried out with previous X-ray satellites might be searched for potential W-R candidates to be further investigated at other wavelengths.

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