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THE CENTRAL X-RAY SOURCE IN RCW 103: EVIDENCE FOR BLACKBODY EMISSION

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ABSTRACT

We present an improved position for the compact X-ray source in the center of the young supernova remnant RCW 103. Only one star brighter than $V \sim 22$ mag lies inside the new error circle, but a spectroscopic study of the star rules out any relationship to the X-ray source. A sensitive search for radio pulsations from RCW 103 has proved equally unsuccessful. The absence of an optical or radio counterpart for the central X-ray source strengthens the likelihood that the object is a hot neutron star emitting blackbody radiation. This result is in accord with several theoretical calculations of neutron star cooling rates.

Subject headings: nebulae: individual — nebulae: supernova remnants — stars: neutron — X-rays: sources

I. INTRODUCTION

X-ray images are now available for more than 50 supernova remnants (SNRs). In view of the expected association of neutron stars with SNRs, it is surprising that unresolved X-ray sources have been detected in only a few cases (Helfand 1981*a*). Apart from the well-known example of PSR 0531+21 in the Crab Nebula, point X-ray sources have been detected in the following SNRs: Vela X(PSR 0833−45; Harnden 1980), W50 (SS 433; Clark and Murdin 1978 and Seward *et al.* 1980), G109.1−1.0 (1E 2259+586; Fahlman and Gregory 1981), and G320.4−1.2 (Seward and Harnden 1982, PSR 1509−58; Manchester, Tuohy, and D'Amico 1982). SS 433 and 1E 2259+586 are both believed to be members of binary systems where the X-ray emission arises from accretion onto the compact objects. Centrally condensed X-ray emission, suggestive of the presence of point sources, has also been observed from three Crab-like SNRs: 3C 58 and CTB 80 (Becker, Helfand, and Szymkowiak 1982) and G74.9+1.2 (Wilson 1980). These sources, if genuine, are presumably similar to PSR 0531+21 in which the X-ray emission is produced in the magnetosphere of a rapidly rotating neutron star. Finally the X-ray point source 1E 161348−5055.1 in the relatively young SNR RCW 103 seems most likely to originate from a neutron star at the center of the remnant (Tuohy and Garmire 1980).

The weakness of the X-ray emission from 1E 161348−5055.1 precluded any attempt to classify the object; in particular, a search for X-ray pulsations was not feasible. Two possible models were discussed by Tuohy and Garmire (1980), namely blackbody radiation from the surface of a hot ($\sim 2 \times 10^6$ K) neutron star and X-ray pulsar emission similar to PSR 0531+21. A third possibility, an SS 433-type binary system, was not considered likely based on luminosity and age arguments. In order to resolve the nature of 1E 161348−5055.1, we have conducted a search for an optical and radio counterpart, aided by an improved X-ray position that has recently become available. The results of these studies are presented in this paper.

II. X-RAY POSITION

The original observation of RCW 103 with the *Einstein Observatory* High Resolution Imager (HRI) produced a position for the central X-ray source accurate to 10″. A detailed understanding of the systematic errors associated with HRI observations has recently allowed the error radius to be reduced to 3″.3 (90% confidence). The new position, which is consistent with the original coordinates, is $\alpha = 16^h13^m48^s.3$, $\delta = -50°55'04''.9$ (1950.0).

Only one star brighter than $V \sim 22$ mag is visible within the new error circle, namely star A in the finding chart of Tuohy and Garmire (1980). The position of star A has been measured to a precision of ~ 0″.5 by PDS astrometry of the ESO blue plate (no. 225) using a surrounding grid of 15 SAO reference stars, and is $\alpha = 16^h13^m48^s.0$, $\delta = -50°55'05''.1$ (1950.0). The angular separation between star A and the X-ray centroid is 2″.9.

III. OPTICAL OBSERVATIONS

We have secured a low-resolution (~ 10 Å) spectrum of star A using the RGO spectrograph with the image photon counting system on the 3.9 m Anglo-Australian Telescope. The spectrum, of 8000 s duration, has been

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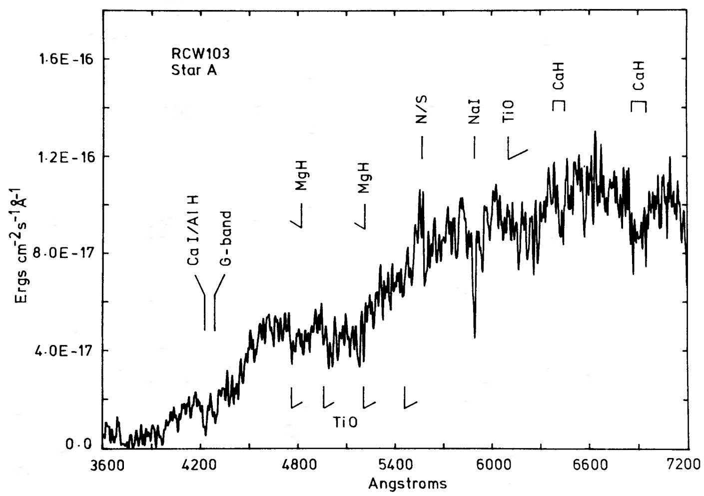

FIG. 1.—Calibrated AAT spectrum of star A in the error circle of the RCW 103 point X-ray source. The features indicated are consistent with those of an extreme subdwarf M star.

calibrated against a white dwarf standard and is shown in Figure 1. *UBVR* measurements from the spectrum yield $V = 19.3$, $U - B = 1.0$, $B - V = 1.6$, and $V - R = 0.8$.

The spectrum of star A is clearly late-type. Specifically, we classify the object as an extreme subdwarf M star on the basis of the spectral features identified in Figure 1 which closely resemble those of LHS 3382 (Ake and Greenstein 1980). Although the star is of interest because of its low metallicity, the spectrum has no emission lines or other unusual features which would support its association with the RCW 103 X-ray source. Normal M star X-ray emission from star A is not consistent with the observed HRI flux of $F_x = 7 \times 10^{-13}$ ergs cm^{-2} s^{-1} (Tuohy and Garmire 1980) in view of the corresponding low *V*-band flux of $F_v = 4.4 \times 10^{-14}$ ergs cm^{-2} s^{-1} (derived from Allen 1973). The ratio, $\log(F_x/F_v) = 1.2$, is two to three orders of magnitude above the level expected for an M star (Vaiana *et al.* 1981). Furthermore, the absolute *V* magnitude of an extreme subdwarf M star is ~ 12.5 based on data for VB 12 (Bessell 1982), which implies a distance to star A of ~ 230 pc. This is substantially less than the distance to RCW 103 of $\gtrsim 3.3$ kpc (Caswell *et al.* 1980). In summary, therefore, we rule out star A as a viable counterpart of the central X-ray source in RCW 103.

IV. RADIO OBSERVATIONS

In an effort to determine whether 1E 161348−5055.1 could be an X-ray pulsar, we undertook a search for pulsed radio emission at the position of the X-ray source using the 64 m Parkes radio telescope. The observing frequency was 1405 MHz which gave a beam size of 15′ FWHM and thus included the entire radio remnant (Caswell *et al.* 1980). Observations were made on three separate occasions, one in 1980 January and two others with greater sensitivity in 1981 November and 1982 March (cf. Manchester, Tuohy, and D'Amico 1982). For the 1980 observations, a single-channel receiver with a room-temperature FET preamplifier having a system temperature of ~ 80 K and predetection bandwidth of 5 MHz was used. The 1981 and 1982 observations were part of a systematic search for pulsars associated with supernova remnants (to be reported separately) and used a dual-channel receiver with cryogenically cooled FET preamplifiers having a system temperature of ~ 45 K on cold sky. For each polarization channel the signal was split into four adjacent 5 MHz bands which were independently detected and sampled. The effective sampling interval for all sessions was 2 ms and integration times were 10–60 minutes. Several independent observations were obtained in each session, and the data were searched for common periodicities. No significant pulsations were detected. The best limits come from the 1981–1982 observations, namely an upper limit of ~ 1.5 mJy on the mean flux density of a pulsar with period between 20 ms and 4 s, duty cycles between 6% and 50%, and dispersion measure less than 1800 cm^{-3} pc. This limit can be compared with the detection threshold for the Molonglo pulsar survey of 15 mJy at 408 MHz (Manchester *et al.* 1978).

V. DISCUSSION

The absence of a viable optical counterpart brighter than $V \sim 22$ mag in the error circle for 1E 161348−5055.1 implies a ratio of $F_x/F_v \gtrsim 200$. There are only three types of galactic X-ray sources which could conceivably have such a high X-ray to optical luminosity: a binary X-ray system containing either a neutron star or a black hole (e.g., Patterson 1981; Lewin and van Paradijs 1981), a nonbinary X-ray pulsar (similar to the Crab pulsar and not powered by accretion), or a hot neutron star emitting blackbody radiation.

The binary X-ray source possibility can be rejected immediately, using an argument similar to that of Helfand (1981*b*). Briefly, the X-ray luminosity of such a system (10^{36}–10^{38} ergs s^{-1}) would require that 1E 161348−5055.1 be at a distance $\gg 10$ kpc, well beyond RCW 103. Also, the interstellar absorption at such a distance would be incompatible with the soft X-ray spectrum observed from RCW 103 by *HEAO 1* (Tuohy *et al.* 1979).

The second possibility, an X-ray pulsar, also seems unlikely but cannot be ruled out. In Table 1 we give the luminosity at radio (10^8–10^9 Hz), IR-optical (10^{14}–10^{15} Hz), and X-ray (1.0–10 keV) frequencies of the pulsed emission from PSR 0531+21, PSR 0833−45, PSR 1509−58, and from the source in RCW 103 interpreted as a pulsar. The distances of the four objects are taken as 2.0, 0.5, 4.2, and 3.3 kpc, respectively. For PSR 0531+21, PSR 0833−45, and PSR 1509−58, the radiation is assumed to be emitted in a beam of diameter equal to the observed pulse duty cycle. For 1E 161348−5055.1, typical parameters are assumed: optical duty cycle 0.1, optical spectral index 0.0, radio duty cycle 0.05, and radio spectral index −2.0. The value assumed for the radio index (α) provides a worst case limit, since our 1405 MHz observation and the nondetection of a pulsar during the 408 MHz Molonglo survey (Manchester *et al.* 1978) requires that $\alpha \geq -2.0$. An index of $\alpha = -2.0$ is reasonably typical for pulsars and is intermediate between that of PSR 0833−45 ($\alpha = -1.2$) and the extreme case of PSR 0531+21 ($\alpha = -3.5$).

The derived limit on pulsed optical emission from 1E 161348−5055.1 falls midway between the values for PSR 0531+21 and PSR 0833−45. This quantity is believed to be a strong function of pulsar period (Wallace *et al.* 1977). The age of RCW 103 lies in the range 1000–3000 years (Tuohy and Garmire 1980; Clark and Caswell 1976), intermediate between that of the Crab and Vela supernova remnants, so a pulsar might also be expected to have an intermediate period and hence intermediate luminosity. Our radio limit for 1E 161348−5055.1 is below the luminosities of both PSR 0531+21 and PSR 0833−45, and it is comparable to that of PSR 1509−58. It is of course possible that we are not swept by the radio beam since, for the known cases, the radio beam is narrower than the optical or X-ray beam. A further argument against the pulsar interpretation, however, is that PSR 0531+21, PSR 0833−45, and PSR 1509−58 are each surrounded by regions of diffuse X-ray emission (Harnden *et al.* 1979; Harnden 1980; Helfand 1981*b*; Seward and Harnden 1982); such emission, which is presumably due to the embedded pulsar, is not evident near 1E 161348−5055.1.

The third and most plausible model for 1E 161348−5055.1 is a hot neutron star emitting black-body radiation. The observed X-ray source is consistent with a star of radius ~ 10 km and surface temperature $\sim 2 \times 10^6$ K at a distance of 3.3 kpc. The absence of an optical candidate brighter than $V \sim 22$ mag in the X-ray error circle is immediately understandable since a neutron star at this temperature would have a broad-band (3000–10,000 Å) magnitude of > 25 (Helfand, Chanan, and Novick 1980). The blackbody interpretation also has theoretical support; the temperature-age data point for 1E 161348−5055.1 agrees closely with predicted cooling curves of a hot neutron star composed of "standard" material (Tsuruta 1980; Glen and Sutherland 1980; van Riper and Lamb 1981; Nomoto and Tsuruta 1981). We conclude therefore, based on the optical, radio, and theoretical evidence, that 1E 161348−5055.1 is most likely a hot neutron star.

The RCW 103 point source represents the strongest case so far for the detection of blackbody emission from a neutron star associated with an SNR. Thermal emission is suspected from both PSR 0531+21 and PSR 0833−45, but in these cases the origin of the X-ray emission is ambiguous owing to the difficulty of disentangling a thermal component from the pulsed nonthermal radiation in the case of PSR 0531+21 (Harnden *et al.* 1979; Helfand 1981*a*) and from the nonthermal nebular component in the case of PSR 0833−45 (Harnden 1980; Helfand 1981*a*). Searches for hot neutron stars in the young historical SNRs have proved negative, and in at least one case (SN 1006), the quoted upper limit ($T < 0.8 \times 10^6$ K) on the surface temperature is significantly below predicted cooling curves (Helfand 1981*a*). We note however that the detection of thermal X-ray emission from several isolated radio pulsars has been reported recently by Helfand (1981*b*). For one of these, PSR 1055−52, the limit on X-ray pulsations is < 15%, providing good evidence that the emission is not non-thermal emission originating in the pulsar magnetosphere.

More definitive observations of the RCW 103 point source will be difficult for the foreseeable future in view

TABLE 1

LUMINOSITIES OF PULSED EMISSION (ergs s^{-1})

Object	Radio	Optical	X-Ray
PSR 0531+21	3×10^{30}[a]	4×10^{33}[b]	2×10^{35}[c]
PSR 0833−45	1×10^{29}[a]	1×10^{29}[b]	$< 1 \times 10^{33}$[c]
PSR 1509−58	4×10^{28}[d]	$< 1 \times 10^{31}$[e,f]	$\sim 5 \times 10^{34}$[e]
1E 161348−5055.1	$< 5 \times 10^{28}$[g]	$< 1 \times 10^{31}$[g,f]	$\sim 1 \times 10^{34}$[c]

[a] Manchester and Taylor 1981.
[b] Manchester 1980.
[c] Tuohy and Garmire 1980 and references therein.
[d] Manchester, Tuohy, and D'Amico 1982.
[e] Seward and Harnden 1982.
[f] Assumes $V \gtrsim 22$ mag.
[g] This work.

of its low intensity. A sensitive CCD search of the error circle could be made, but identification of an optical counterpart may be beyond even the capability of Space Telescope. Regular X-ray monitoring of the object (e.g., with EXOSAT) should be undertaken to determine whether the X-ray flux remains constant on a time scale of months, as expected for a blackbody source.

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