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X-RAY VARIABILITY FROM THE COMPACT SOURCE IN THE SUPERNOVA REMNANT RCW 103

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ABSTRACT

A new *ASCA* observation of 1E 161348−5055, the central compact X-ray source in the supernova remnant RCW 103, reveals an order-of-magnitude decrease in its 3–10 keV flux since the previous *ASCA* measurement 4 yr earlier. This result is difficult to reconcile with suggestions that the bulk of the emission is simple quasi-blackbody, cooling radiation from an isolated neutron star. Furthermore, archived *Einstein* and *ROSAT* data sets spanning 18 yr confirm that this source manifests long-term variability, to a lesser degree. This provides a natural explanation for difficulties encountered in reproducing the original *Einstein* detection of 1E 161348−5055. Spectra from the new data are consistent with no significant spectral change despite the decline in luminosity. We find no evidence for a pulsed component in any of the data sets, with a best upper limit on the pulsed modulation of 13%. We discuss the phenomenology of this remarkable source.

Subject headings: stars: individual (1E 161348−5055) — stars: neutron — supernova remnants — supernovae: individual (RCW 103) — X-rays: stars

1. INTRODUCTION

Recent spectro-imaging X-ray observations of central compact sources in supernova remnants (SNRs) challenge earlier notions that most young neutron stars (NSs) evolve in a manner similar to the prototypical Crab pulsar (Gotthelf 1999). In fact, the latest compilations show that most of such associated objects manifest properties distinct from those of the Crab-like systems.

Based on observational grounds alone, three classes of NSs in SNRs are known whose flux is dominated by their X-ray emission; these include the X-ray pulsars with anomalously slow rotation (periods in the range of 5–12 s) and steep ($\Gamma \gtrsim 3$) power-law spectra (Gregory & Fahlman 1980; Gotthelf & Vasisht 1998, and references therein), the soft gamma-ray repeaters (Cline et al. 1982; Kulkarni et al. 1994; Vasisht et al. 1994), and a population of radio-quiet NSs in remnants (Caraveo et al. 1996; Petre, Becker, & Winkler 1996; Mereghetti, Bignami, & Caraveo 1996). The above objects are linked by their apparent radio-quiet nature and, taken collectively, may help further reconcile the NS birth rate with the observed SNR census. In this study, we focus on the enigmatic X-ray source 1E 161348−5055 in the SNR RCW 103, for which no clear interpretation yet exists within the above taxonomic framework.

The *Einstein* X-ray source 1E 161348−5055 lies near the projected center of the bright, young ($\sim 2 \times 10^3$ yr; Carter, Dickel, & Bomans 1997) Galactic shell–type SNR RCW 103 (G332.4-0.4) and has been proposed as the first example of an isolated, cooling NS (Tuohy & Garmire 1980). It was discovered using the high-resolution imager (HRI) but went unseen by a prior *Einstein* IPC observation and a subsequent *ROSAT* Position-Sensitive Proportional Counter (PSPC) one, supposedly because of the poorer spatial resolution of these instruments. Surprisingly, an initial observation with the *ROSAT* HRI also failed to detect the source; this was attributed to the reduced HRI sensitivity of the 10′ off-axis pointing (Becker 1993). Finally, a 1993 *ASCA* observation rediscovered this elusive object (Gotthelf, Petre, & Hwang 1997, hereafter GPH97), but its spectral characteristics were found to be incompatible with a simple cooling NS model. This redetection has been confirmed by more recent, on-axis, *ROSAT* HRI observations.

Here, we present the results of our follow-up (1997 September) *ASCA* observation of 1E 161348−5055. In the same field lies the recently discovered 69 ms pulsar AX J161730−505505 (Torii et al. 1998), whose analysis is presented separately (Torii et al. 1999). While both sources are detected again, the flux from 1E 161348−5055 has declined significantly since the previous *ASCA* measurement. We discuss some implications of this large flux variability on the nature of 1E 161348−5055.

2. OBSERVATIONS AND ANALYSIS

A day-long follow-up observation with *ASCA* (Tanaka, Inoue, & Holt 1994) of RCW 103 was carried out on 1997 September 4. Data were acquired with both the solid-state (SISs) and gas scintillation spectrometers (GISs). The essential properties of these instruments are qualified in GPH97. The SIS data were acquired in 1-CCD BRIGHT mode with 1E 161348−5055 placed as close to the mean SIS telescope bore sight as was practical, to minimize vignetting losses. The GIS data were collected in the highest time-resolution mode (0.5 or 0.064 ms, depending on the telemetry mode), with reduced spectral binning of ∼12 eV per channel. The effective, filtered observation time is 58 (49) ks for each GIS (SIS) sensor. The new data were reduced and analyzed with the same methodology as in GPH97.

3. RESULTS

We compared images of RCW 103 from our new observation with the *ASCA* images obtained 4 yr earlier. The flux-corrected GIS images from the two epochs, restricted to the hard energy bandpass (3–10 keV), are displayed in Figure 1 using an identical intensity scale. Both reveal a pair of distinct features, each having a spatial distribution consistent with that of a point source: one at the position of 1E 161348−5055 and the other at the position of the 69 ms X-ray pulsar AX J161730−505505 (due north); the flux of the latter has evidently remained constant (see Torii et al. 1999 for details). However, we estimate

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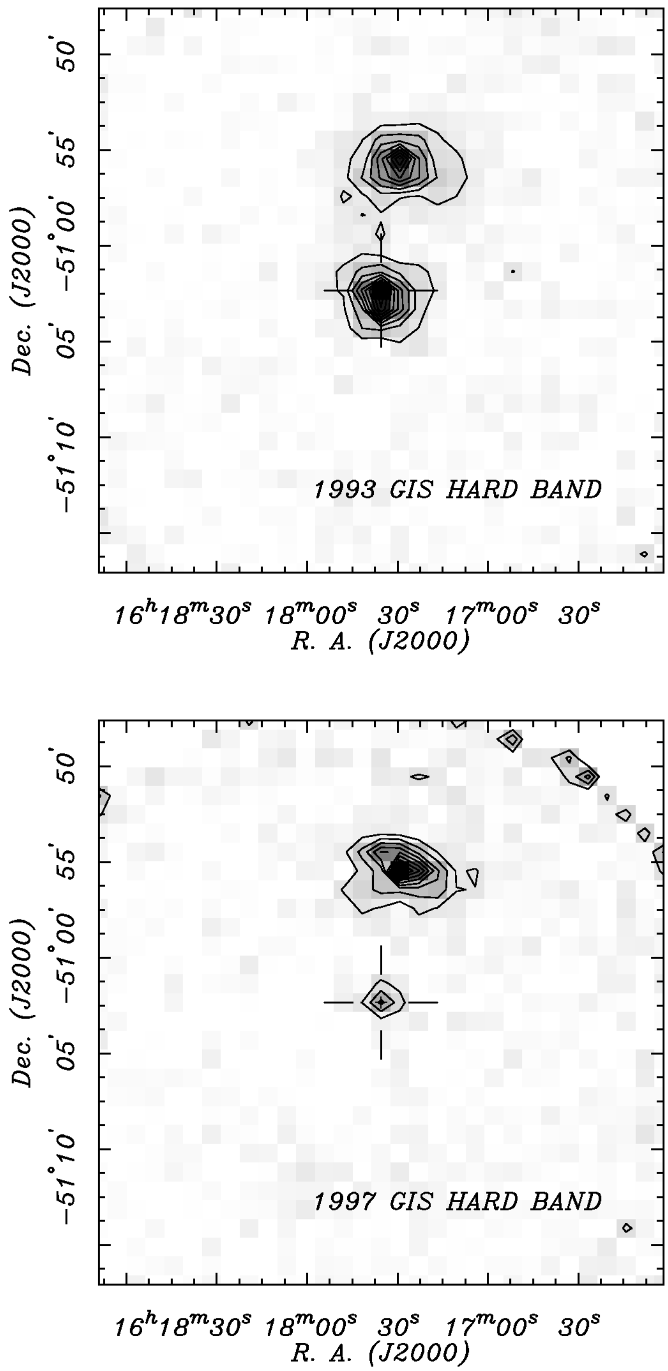

FIG. 1.—*ASCA* GIS images of 1E 161348−5055 (*cross*), the compact point source in RCW 103, taken 4 yr apart (*left:* 1993; *right:* 1997). At the top of the picture is the 69 ms X-ray pulsar AX J161730−505505. These background-subtracted hard energy bandpass (3–10 keV) images are flux corrected and plotted with the same scaling. The central source in RCW 103, 1E 161348−5055, has dimmed by a factor of ~12, while the pulsar flux remained relatively constant. The soft nebula flux from the shell of RCW 103 has been subtracted from these images. Contours along the edge of GIS in the 1997 observation (*upper right corner*) are not significant.

that 1E 161348−5055 has dimmed a factor ≃12 in the hard band, after the diffuse flux from the remnant has been taken into account using the following method.

The soft X-ray flux (below 2 keV) is dominated by steady thermal emission from shock-heated gas in the remnant. The contribution of this component to the hard-band images is estimated using the soft-band images. The latter provides a good model for the spatial distribution of the surrounding shell on arcminute scales in the 3–10 keV range. The soft-band contribution from the shell was renormalized to the hard band and subtracted from the flux-calibrated hard-band image to extract the flux contribution from the source alone. For the comparison, the new data were rebinned by a factor of 4 (~1′ × 1′ pixels) to match the binning used with the earlier observation. The longer exposure of the second observation results in increased sensitivity to 1E 161348−5055; however, this gain is offset by its location at a greater off-axis angle (as is evident by the asymmetrical point-source response) relative to the first observation. An equivalent analysis of the SIS data reproduces the variability seen in the GIS hard band.

TABLE 1

FITS TO *ASCA* SIS SPECTRUM

	1997		1993
MODEL[a]	χ^2 (dof)	kT or Γ[b]	kT or Γ[b]
Diffuse surroundings NEI	390 (227)	0.3	0.3
Source NEI	417 (211)	...	...
NEI+blackbody	260 (209)	$0.63^{+0.08}_{-0.16}$	$0.56^{+0.03}_{-0.03}$
NEI+power law	238 (209)	$3.9^{+0.20}_{-0.30}$	$3.2^{+0.20}_{-0.20}$
NEI+bremsstrahlung	247 (209)	$1.43^{+0.33}_{-0.23}$	$1.6^{+0.20}_{-0.20}$

[a] Nonequilibrium ionization (NEI) model for remnant emission; see GPH97.

[b] Γ is the photon index; kT in units of keV. N_H is fixed to the best fit values of 7.3×10^{21} cm^{-2} (1997) and 6.8×10^{21} cm^{-2} (1993).

3.1. *Spectroscopy*

We analyzed the spectrum from the new observation using the same approach presented in GPH97. To maximize the sensitivity, we simultaneously fit the spectra from all four *ASCA* detectors. We restricted our SIS spectral fits to greater than 1.2 keV since the calibration at the lower energies has become less reliable over time. Despite the lower source flux, fitting the four spectra made it possible to measure the source spectrum with equivalent significance as the earlier analysis (which used only one SIS data set). The resulting fits to simple models (Table 1) are consistent with those inferred for the first observation. Thus, while the flux has decreased by an order of magnitude, the spectrum appears essentially unchanged.

3.2. *The Long-Term Light Curve*

To investigate its long-term flux behavior, we constructed a light curve of 1E 161348−5055 which spans 18 yr (1979–1997), using 10 available archival observations. For each observation, we extracted background-subtracted count rates or 3 σ upper limits. These rates are then used to estimate the flux in a given energy band. For lack of knowledge to the contrary, we assume that the spectral shape is invariant in time and modeled by a blackbody whose parameters are given in Table 1. The best-fit power-law model is unphysical at the softer X-ray energies, and thus the blackbody model is preferred for this comparison. We folded the latter model through the spectral response function of each instrument using the XSPEC spectral fitting package and inferred the source flux for each observation in a fiducial 0.5–2 keV energy band. The results, listed in Table 2 and plotted in Figure 2, confirm a dramatic flux change between the *ASCA* observations and suggest that 1E 161348−5055 is variable, to a lesser extent, among the other observations.

TABLE 2
Log of X-Ray Imaging Observations of RCW 103

Mission/Sensor	Observation Date (UT)	Exposure (ks)	Count Rate[a] (counts ks^{-1})	0.5–2 keV flux[b] (10^{-13} cgs)
Einstein/IPC	1979 Feb 26	2.6	<40	<5.1
Einstein/HRI	1979 Sep 14	3.1	3.8 ± 0.7	4.4 ± 0.7
ROSAT/HRI	1991 Feb 13	5.1	<7.5	<3.2
ROSAT/PSPC	1991 Feb 27	37.2	7.7 ± 2.3	1.1 ± 0.3
ASCA/SIS	1993 Aug 17	47.7	50 ± 10	55 ± 11
ROSAT/HRI	1994 Feb 26	1.1	13 ± 4	6.0 ± 1.7
	1994 Aug 02	4.4	9 ± 2.6	3.8 ± 1.2
	1995 Mar 08	48.1	8.4 ± 0.7	3.6 ± 0.4
	1995 Aug 18	8.1	7.4 ± 1.6	3.1 ± 0.6
ASCA/SIS	1997 Sep 04	58.6	4 ± 1	6 ± 1

[a] Spectral fit bandpass: 0.2–4.5 keV *Einstein*; 0.2–2.4 keV *ROSAT*; 1.2–10 keV *ASCA*.
[b] Flux at earth in ergs cm^{-2} s^{-1}, assuming best-fit blackbody ($kT = 0.63$ keV) and N_H (7.3×10^{21} cm^{-2}) from the second *ASCA* observation. Upper limits are 3 σ.

We present this source flux comparison among instruments with some caution, since these can be potentially unreliable. The different energy bands, flux calibrations, point response functions, and background contamination can produce large uncertainties in the derived fluxes. When extrapolating, the relative count rates are very sensitive to the instrumental energy band, along with the assumed N_H and emission model. However, our fundamental result stands regardless of the aforementioned caveats: the *ASCA* data alone, and to a lesser extent the *ROSAT* data, establish the fact that 1E 161348−5055 varied throughout the time it has been observed.

3.3. *The Short-Term Variability*

The excursions in flux noted from observations separated by months or years suggest that variability might be present on shorter timescales. We searched the day-long *ASCA* observations for hour-scale temporal variability. In addition, we examined the behavior on a timescale of a few days using the 1995 August *ROSAT* HRI observation, with a net exposure time of 50 ks spread over a week. In neither case did we find evidence of variability greater than the photon statistic limit of 10%.

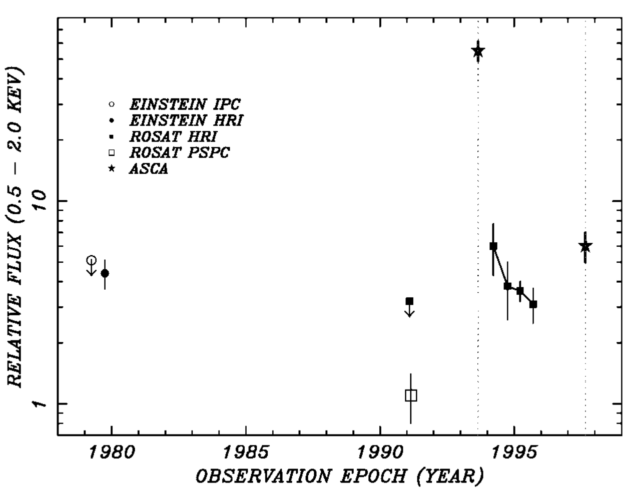

Fig. 2.—Long-term light curve of 1E 161348−5055 in the 0.5–2.0 keV energy bandpass. Symbols represent *Einstein* IPC (*open circle*), *Einstein* HRI (*filled circle*), *ROSAT* PSPC (*open square*) and HRI (*filled squares*), and *ASCA* (*star*). Error bars are 1 σ. The dashed vertical lines indicate the model-dependent uncertainty in the *ASCA* flux when extrapolated to the 0.5–2 keV bandpass.

We searched the new *ASCA* GIS data for a coherent pulsed signal, as in GPH97. No significant periodicity was found in the period space between 10 ms and 1000 s. The upper limit on the pulsed fraction for this data set is ∼23%, compared with the 13% limit of GPH97. The data show no clear evidence for accretion noise such as redness in the power spectrum. The data were searched for X-ray bursts and other anomalies in the light curve, but none were found.

4. DISCUSSION

A number of hypotheses have been advanced to explain the nature of 1E 161348−5055. Upon discovery, this source was proposed as an isolated neutron star emitting blackbody radiation (Tuohy & Garmire 1980). Further optical and radio observations (e.g., Tuohy et al. 1983; Dickel et al. 1996) have failed to identify a counterpart, thereby bolstering this interpretation. The observations of GPH97 showed that the point source could be described as a hot blackbody of $kT \simeq 0.6$ keV with a 5–10 keV luminosity of $L_X \simeq 10^{34}$ ergs s^{-1} (at 3.3 kpc). This implies an effective emitting area of only 1 km^2, a rather small hot spot, corresponding to ∼0.1% of the surface area of an NS. This in turn is surprising since the source shows no rotational modulation (down to ∼13%). Furthermore, the inferred temperature is too high for an object of age a few times 10^3 yr (but see below).

Heyl & Hernquist (1998) recently attempted to salvage the cooling NS model by invoking an ultramagnetized star ($B_s \sim 10^{15}$ G) with an accreted hydrogen atmosphere (see Page 1997 for a review). This combination can enhance the cooling flux as well as shift the emission blueward (Chabrier, Potekhin, & Yakov 1997) so that it effectively mimics a hot blackbody in the *ASCA* spectrum. However, it is hard for cooling models to address the issue of variability or the dramatic flux reduction observed between the *ASCA* epochs, unless there is a source for rejuvenating the heating of the NS interior. Such a source could be the superstrong magnetic field, implicit in the above model.

Energy for impulsive heating of the core could be provided by episodic rearrangement of the magnetic field (Thompson & Duncan 1996) in the stellar interior. The stellar surface would readjust to reflect the internal heating on a short thermal timescale of a few months. Although heating of the NS is viable in this scenario, the rapid cooling on a timescale of a few years, observed between the *ASCA* epochs, cannot be explained without some very ‘‘exotic’’ cooling process. In addition, a factor of 10 variability in the hard (3–10 keV) band would result in a downward shift of the effective temperature by a factor of 1.4, which should have been detected. On these grounds, we reject the hypothesis that the observed X-ray emission from 1E 161348−5055 is simple cooling radiation.

An ultramagnetized NS is also a leading model for the anomalous X-ray pulsars (AXPs), an example of which is the $\lesssim$2000 yr old, 12 s X-ray pulsar in the remnant Kes 73 (Vasisht & Gotthelf 1997). GPH97 compared 1E 161348−5055 to the latter on the basis of similar spectral characteristics. And at least two AXPs are reported to vary significantly in flux, by as much as a factor of 5 (1E 1048.1−593; Oosterbroek et al. 1998). While 1E 161348−5055 shows some properties that are tantalizingly similar to those of the AXPs, the lack of observed strong pulsations (∼30% modulation for the AXPs) is notably amiss, particularly since a large magnetic field should result in highly anisotropic surface emission. Gravitational defocusing and/or unfavorable viewing geometry, however, might account for the apparent lack of pulsations.

Alternatively, the variability can be indicative of an accreting compact object. Popov (1997) suggests that 1E 161348−5055 is an old accreting NS with a low magnetic field and long spin period (∼10^3 s), the by-product of a disrupted binary and not of the same age as RCW 103. This proposition is bolstered by the discovery of the nearby 69 ms pulsar AX J161730−505505 (spin-down age of 8100 yr), located outside the remnant shell (Torii et al. 1998). Several arguments, including those based on the pulsar's implied velocity and lack of wind nebula and the symmetry of the SNR, however, make an association unlikely (Kaspi et al. 1998; Torii et al. 1999).

Finally, there exists the possibility that the source is an isolated stellar-mass black hole (BH), accreting from the surrounding medium or from supernova ejecta fallback. Brown & Bethe (1994) have discussed scenarios in which a massive progenitor explodes as a supernova and then evolves into a BH of several solar masses after accreting captured ejecta. Such a scenario is clearly applicable to the source in RCW 103. Temporal variability and lack of pulsed emission are the natural consequences in such a model.

An accretion process around a BH almost inevitably involves rotating gas flows. Popov (1997) has dismissed the possibility of a few stellar-mass BHs in RCW 103 based on the small implied emitting area (∼1 km^2) of an equivalent blackbody radiator (see § 4). This argument would certainly apply for the case of the standard optically thick, thin-disk model. However, low-efficiency solutions can exist for accretion flows (especially at low $\dot{M}$) around BHs, in which most of the viscously generated thermal energy is advected into the BH. Below a critical mass accretion rate of ∼$0.1\dot{M}_{\rm Edd}$ ($\dot{M}_{\rm Edd}$ is the Eddington rate), accretion flows turn advection dominated (or ADAF), and the observed luminosity in 1E 161348−5055 would suggest an accretion rate of $10^{-2.5}\dot{M}_{\rm Edd}$ to $10^{-3.0}\dot{M}_{\rm Edd}$ (or ∼10^{-10} $M_\odot$ yr^{-1}) (see ADAF models summarized in Narayan, Mahadevan, & Quataert 1999). At this rate, the BH would accrete ∼10^{-7} $M_\odot$ of matter, a small fraction of the mass of supernova ejecta, at the sustained present rate over its lifetime of ∼10^3 yr. Within the framework of the above arguments, it is possible that flow around 1E 161348−5055 could be detected as a faint optical source ($V \gtrsim 22$ after accounting for visual extinction) or a 10–100 μJy (1 GHz) radio source.

5. CONCLUSIONS

The variability of the X-ray emission from the compact source in RCW 103 leaves little room for a conventional cooling NS origin. Instead, an accretion scenario may be considered, although the relatively low luminosity, lack of any optical counterpart, and young age are inconsistent with a typical accreting NS binary. Accretion from a very low mass ($\lesssim$0.1 $M_\odot$) companion (Mereghetti et al. 1996; Baykal & Swank 1996) or a fossil disk around a solitary NS (van Paradijs et al. 1995), however, is not ruled out. We suggest that within the context of inefficient accretion (such as advection-dominated flows), a stellar mass black hole is a viable possibility. We reiterate, however, that the spectral characteristics of 1E 161348−5055 are remarkably similar to those of the AXPs, which are suspected to be ultramagnetized NSs and thought to be powered by magnetic field decay rather than by rotational braking (Thompson & Duncan 1996; Vasisht & Gotthelf 1997).

Independent of the above phenomenology, the properties of 1E 161348−5055 add to the view that young collapsed stars can follow an evolutionary scenario quite distinct from those of Crab-like pulsars. The property of being radio quiet is common to all AXPs, soft gamma-ray repeaters, and to 1E 161348−5055 (Gotthelf 1999; for possible physical mechanisms, see Baring & Harding 1998). It is likely that they all share a common heritage and may prove to be part of an evolutionary sequence.

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