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

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Draft of Jan 1999

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 four years earlier. This result is hard 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 datasets spanning 18 years 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 percent. We discuss the phenomenology of this remarkable source.

Subject headings: stars: individual (1E 161348–5055) — stars: neutron — supernova remnants: 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 1998). In fact, the latest compilations shows 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 (with periods in the range of 5 – 12 s) and steep (Γ ≥ 3) power-law spectra (Gregory & Fahlman 1980; Gotthelf & Vasisht 1998 and refs. 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 et al. 1996; Mereghetti et al. 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 (~ 2 × 10^3 yrs; Carter et al. 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 PSPC one, supposedly due to 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 re-discovered this elusive object (Gotthelf, Petre & Hwang 1997, GPH97 herein), but its spectral characteristics were found to be incompatible with a simple cooling NS model. This re-detection has been confirmed by more recent, on-axis, ROSAT HRI observations.

Herein, we present the results of our follow-up (Sep 1997) 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 the ASCA Observatory (Tanaka et al. 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 ms or 0.064 ms, depending on the telemetry mode), with reduced spectral binning of ~ 12 eV per PHA 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 four years earlier. The flux-corrected GIS images from the two epochs, restricted to the hard energy band-pass (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 J161730-5055.
505505 (due north); the flux of the latter has evidently remained constant (see Torii et al. 1999 for details). However, we estimate that 1E 161348–5055 has dimmed a factor $\approx 12$ 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 (as is evident by the asymmetrical PSF) relative to the first observation. An equivalent analysis of the SIS data reproduces the variability seen in the GIS hard band.

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 $>1.2$ keV as the calibration at the lower energies has become less reliable over time. The improved viewing geometry over the previous observation, coupled with the spectral stacking (four detectors), made it possible to measure the spectrum, despite the lower source flux (only one SIS data set was used in the earlier spectral analysis). 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 years (1979–1997), using 10 available archival observations. For each observation, we extracted background-subtracted countrates or 3 light curve of 1E 161348–5055 which spans 18 years. The long 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 PSF) relative to the first observation. An equivalent analysis of the SIS data reproduces the variability seen in the GIS hard band.

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 time-scales. 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 August, 1995, 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 percent.

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 - 1000 s. The upper limit on the pulsed fraction for this data set is $\approx 23\%$, 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 $kT \approx 0.6$ keV and a $0.5–10$ keV flux of $6.5 \times 10^{34}$ erg cm$^{-2}$ s$^{-1}$; therefore, a luminosity of $L_X \approx 10^{38}$ erg s$^{-1}$ (at 3.3 kpc) and an effective emitting area of $1 \text{ km}^2$, or $\approx 0.1\%$ the surface area of a NS. This corresponds to a rather small hot-spot on a stellar surface, which is in turn surprising since the source shows no rotational modulation (down to ~ $13\%$). Also, the inferred temperature is too high for an object of age few $\times 10^7$ yrs (but see below).

Heyl & Hernquist (1998) recently attempted to salvage the cooling NS model by invoking an ultra-magnetized star ($B \sim 10^{15}$ G) with an accreted hydrogen atmosphere (Page 1997, for a review). This combination can enhance the cooling flux as well as shift the emission bluewards (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 flux decimation observed between the ASCA epochs, unless there is a source for rejuvenating the heating of the NS interior. Such a source could be the super-strong magnetic field, implicit in the above model. Episodic rearrangement of the field (Thompson & Duncan 1996) in the stellar interior could provide the energy to impulsively heat the core.

The stellar surface would re-adjust 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 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 ultra-magnetized NS is also a leading model for the anomalous X-ray pulsars (AXPs), an example of which is the 1E 161348−5055. 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 five (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 as a large magnetic field should result in highly anisotropic surface emission. Gravitational defocusing and/or unfavorable viewing geometry, however, might account for the lack of observed 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 yrs), 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 fall-back. 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 BH 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 M) around BHs, in which most of the viscously generated thermal energy is advected into the BH. Below a critical mass accretion rate of ∼0.1M_{Edd} (M_{Edd} is the Eddington rate) accretion flows turn advection dominated (or ADAF), and the observed luminosity in 1E161348−5055 would suggest an accretion rate of 10^{-2.5} - 3.0M_{Edd} (or ∼10^{-10} M_{sun} yr^{-1}) (cf ADAF models summarized in Narayan et al. 1998). At this rate, the BH would accrete ∼10^{-7} M_{sun} of matter, a small fraction of the mass of supernova ejecta, at the sustained present rate over its lifetime of ∼10^7 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 ≥ 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 optical counterpart, and young age are inconsistent with a typical accreting NS binary. Accretion from a very low mass (<0.1 M_{sun}) 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 1E161348−5055 are remarkably similar to those of the AXPs, which are suspected to be ultra-magnetized NSs and thought to be powered by magnetic field decay rather than rotational braking (Thompson & Duncan 1996; Vasishit & Gotthelf 1997).

Independent of the above phenomenology, the properties of 1E161348−5055 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, SGRs and to 1E 161348−5055 (Gotthelf 1998; 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.

This work uses data made available from the HEASARC public archive at GSFC. G.V. thanks J Heyl for discussions.

REFERENCES

Gotthelf, E.V. 1996, in “Workshop on the relationship between NS & SNRs,” Memorie della Società Astronomica Italiana
### Table 1

**Fits to ASCA SIS Spectrum**

<table>
<thead>
<tr>
<th>Model</th>
<th>$\chi^2$(DoF)</th>
<th>$kT$ or $\Gamma^b$</th>
<th>$kT$ or $\Gamma^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffuse Surroundings</td>
<td>390 (227)</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>NEI</td>
<td>417 (211)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NEI + BB</td>
<td>260 (209)</td>
<td>0.63$^{+0.71}_{-0.59}$</td>
<td>0.56$^{+0.59}_{-0.59}$</td>
</tr>
<tr>
<td>NEI + PL</td>
<td>238 (209)</td>
<td>3.0$^{+1.5}_{-1.3}$</td>
<td>3.5$^{+1.3}_{-1.2}$</td>
</tr>
<tr>
<td>NEI + BREM</td>
<td>247 (209)</td>
<td>1.43$^{+0.16}_{-0.14}$</td>
<td>1.61$^{+0.14}_{-0.14}$</td>
</tr>
</tbody>
</table>

*See GPH97 for details.

* $\Gamma$ is the photon index; $kT$ in units of keV. $N_H$ is fixed to the best fit values of $7.3 \times 10^{21}$ cm$^{-2}$ (1997) and $6.8 \times 10^{21}$ cm$^{-2}$ (1993).

### Table 2

**Log of X-ray Imaging Observations of RCW 103**

<table>
<thead>
<tr>
<th>Mission/Sensor</th>
<th>Obs. Date</th>
<th>Expos. (ks)</th>
<th>Cnt rate$^a$ (cps)</th>
<th>5–2 keV flux$^b$ (10$^{-13}$ cgs)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Einstein</em> / IPC</td>
<td>79/02/26</td>
<td>2.6</td>
<td>&lt;40</td>
<td>&lt;5.1</td>
</tr>
<tr>
<td><em>Einstein</em> / HRI</td>
<td>79/09/14</td>
<td>3.1</td>
<td>3.8±0.7</td>
<td>4.4±0.7</td>
</tr>
<tr>
<td><em>ROSAT</em> / HRI</td>
<td>91/02/13</td>
<td>5.1</td>
<td>&lt;7.5</td>
<td>&lt;3.2</td>
</tr>
<tr>
<td><em>ROSAT</em> / PSPC</td>
<td>91/02/27</td>
<td>37.2</td>
<td>7.7±2.3</td>
<td>1.1±0.3</td>
</tr>
<tr>
<td><em>ASCA</em> / SIS</td>
<td>93/08/17</td>
<td>47.7</td>
<td>50±10$^c$</td>
<td>55±11</td>
</tr>
<tr>
<td><em>ROSAT</em> / HRI</td>
<td>94/02/26</td>
<td>1.1</td>
<td>13±4</td>
<td>6.0±1.7</td>
</tr>
<tr>
<td><em>ROSAT</em> / HRI</td>
<td>94/08/02</td>
<td>4.4</td>
<td>9±2.6</td>
<td>3.8±1.2</td>
</tr>
<tr>
<td><em>ROSAT</em> / HRI</td>
<td>95/03/08</td>
<td>48.1</td>
<td>8.4±0.7</td>
<td>3.6±0.4</td>
</tr>
<tr>
<td><em>ROSAT</em> / HRI</td>
<td>95/08/18</td>
<td>8.1</td>
<td>7.4±1.6</td>
<td>3.1±0.6</td>
</tr>
<tr>
<td><em>ASCA</em> / SIS</td>
<td>97/09/04</td>
<td>58.6</td>
<td>4±1$^c$</td>
<td>6±1</td>
</tr>
</tbody>
</table>

* Spectral fit band-pass: 0.2–4.5 keV *Einstein*; 0.2–2.4 keV *ROSAT*; 1.2–10 keV *ASCA*.

* Flux at earth in ergs cm$^{-2}$ s$^{-1}$, assuming best fit blackbody (kT=0.63 keV) and $N_H$ ($7.3 \times 10^{21}$ cm$^{-2}$) from the second *ASCA* observation. Upper limits are 3$\sigma$. 

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X-ray Variability from RCW 103
FIG. 1.— ASCA GIS images of 1E 161348–5055 (cross), the compact point source in RCW 103, taken 4 years 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 band-pass (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 $\sim 12$, 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.

FIG. 2.— The long term light curve of 1E 161348–5055 in the 0.5–2.0 keV energy band-pass. Symbols represent: Einstein IPC (open circle); Einstein HRI (filled circle); ROSAT PSPC (open square), HRI (filled squares); and ASCA (star). Error bars are one sigma. The dashed vertical lines indicate the model dependent uncertainty in the ASCA flux when extrapolated to the 0.5–2 keV band-pass.