SEARCH FOR A NEAR-INFRARED COUNTERPART TO THE CASIOPEIA A X-RAY POINT SOURCE

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ABSTRACT

We report deep near-infrared and optical observations of the X-ray point source in the Cassiopeia A supernova remnant, CXO J232327.9+584842. We have identified a $J = 21.4 \pm 0.3$ mag and a $K_s = 20.5 \pm 0.3$ mag source within the 1 $\sigma$ error circle, but we believe this source is a foreground Population II star with $T_{\text{eff}} = 2600$–2800 K at a distance of $\approx 2$ kpc that could not be the X-ray point source. We do not detect any sources in this direction at the distance of Cas A and therefore place 3 $\sigma$ limits of $R \geq 25$ mag, $F_{675W} \geq 27.3$ mag, $J \geq 22.5$ mag, and $K_s \geq 21.2$ mag (and roughly $H \geq 20$ mag) on emission from the X-ray point source, corresponding to $M_R \geq 8.2$ mag, $M_{F675W} \geq 10.7$ mag, $M_J \geq 8.5$ mag, $M_H \geq 6.5$ mag, and $M_{K_s} \geq 8.0$ mag, assuming a distance of 3.4 kpc and an extinction of $A_V = 5$ mag.

Subject headings: infrared; stars — stars: late-type — supernovae: individual (Cassiopeia A)

1. INTRODUCTION

Cassiopeia A (Cas A) is the youngest Galactic supernova remnant, with an age of $\approx 320$ yr, and according to Ashworth (1980) it is associated with the explosion observed by Flamsteed (1725) in 1680. Hughes et al. (2000) have found that the elemental abundances in Cas A are consistent with those expected from the remnant of a massive star, possibly a Wolf-Rayet star (Fesen, Becker, & Blair 1987), and therefore Cas A is considered to have been a Type II supernova. One therefore expects a compact central remnant such as a neutron star or black hole, based on the initial mass function of Type II supernovae (e.g., de Donder & Vanbeveren 1998). From the first light images of the Chandra X-Ray Observatory (CXO), Tananbaum (1999) reported detection of a compact source located at the apparent center of Cas A. The detection of this source, CXO J232327.9+584842 (hereafter the X-ray point source or XPS), was later confirmed in archival ROSAT (Aschenbach 1999) and Einstein (Pavlov & Zavlin 1999) data.

The XPS is located within 5" of the expansion center of Cas A (van den Bergh & Kamper 1983), and given the space density of active galactic nuclei (AGNs), the chance of finding one within this distance of the center is quite small. We convert the count rates from Chakrabarty et al. (2001) to the 0.5–2.4 keV band and get an absorbed flux of $\approx 4 \times 10^{-13}$ ergs $s^{-1} \ cm^{-2}$. Comparing this with the AGN log $N$–log $S$ relation from Georgantopoulos et al. (1996), we would expect $\sim 0.4$ AGN deg$^{-2}$, or $\sim 2 \times 10^{-6}$ AGN, of this flux at the center of Cas A. It is therefore extremely improbable that the XPS is an AGN, a fact further confirmed by its relatively steep spectrum (Chakrabarty et al. 2001).

Therefore it is generally believed that the XPS is associated with the remnant of the Cas A progenitor (Chakrabarty et al. 2001). The X-ray spectrum of the XPS, as determined by Pavlov et al. (2000) and Chakrabarty et al. (2001), can be fitted by a power law with a photon index of $\approx 3$. Other acceptable fits include thermal bremsstrahlung ($kT_e \approx 1.7$ keV), blackbody ($kT_e \approx 0.5$ keV, $R_e \approx 0.5$ km), or neutron star atmospheres ($kT_e \approx 0.4$ keV, $R_e \approx 0.8$ km for the model of Heyl & Hernquist 1998; $kT_e \approx 0.27$ keV, $R_e \approx 2$ km for the model of Zavlin, Pavlov, & Shibanov 1996).

The nature of the XPS is unclear. However, we have an idea as to what it is not. The spectral index of the XPS is significantly steeper than those typical of young X-ray pulsars; its luminosity is $\geq 10^2$ times less than those of young X-ray pulsars, and there is no evidence for a synchrotron nebula (McLaughlin et al. 2001). The spectrum is similar to that of an anomalous X-ray pulsar (AXP; see Mereghetti 2000), but the X-ray luminosity is at least several (if not 10–100) times fainter than that typical for AXPs. The XPS is cooler but much more luminous than isolated neutron stars (Motch 2000).

Furthermore, there have not been any detections of optical (van den Bergh & Pritchett 1986; Ryan, Wagner, & Starrfield 2001) or radio (McLaughlin et al. 2001, and references therein) emission from the XPS, nor have X-ray pulsations been detected (Chakrabarty et al. 2001), although the current limits are not very constraining. Therefore the XPS is almost certainly not a young pulsar similar to the Crab. Theories as to its identity range from a cooling neutron star emitting from polar caps to an accreting black hole (Umeda et al. 2000; Pavlov et al. 2000).

From measures of line ratios in the Cas A remnant, Searle (1971) found the extinction to be $A_V = 4.3$ mag in the direction of one filament. Later radio studies found significant variations of $A_V$ on scales of $\sim 1$' and overall values ranging from 4–5 mag for the north and northeastern rim and $\geq 5$–6 mag for the rest of the supernova remnant (Troland, Crutcher, & Heiles 1985). Similarly, Hurford & Fesen (1996) found extinction values of 4.6–5.4 mag across the northern portion (assuming $R_V = 3.1$). We will therefore adopt a middle value of $A_V \approx 5$ mag. We assume that Cas A and the XPS are at a distance of $3.4 \pm 0.1$ kpc (Reed et al. 1995), which we parameterize as $D = 3.4d_{1.4}$ kpc.

In this paper we report on optical/near-infrared searches for a counterpart to the XPS. We believe that given the unknown nature of the XPS, searches at all wavelengths are warranted, and even upper limits may constrain the nature of this enigmatic source. The paper is organized as follows:
in § 2 we detail our observations and reduction techniques, § 3 contains a description of the results, and § 4 presents an analysis of these results. Finally, a discussion and conclusions are provided in § 5.

2. OBSERVATIONS

2.1. Cas A Central Point-Source Position

The supernova remnant Cas A was observed several times with CXO. After the initial detection in the first-light images (Tananaua 1999), a long High-Resolution Camera I (HRC-I) observation was obtained on 1999 December 20, and a third observation with the HRC-S in imaging mode was taken on 2000 October 5. A discussion of the results from this observation is in preparation (S. S. Murray et al. 2001, in preparation); here we provide only the source location information. Table 1 gives the point-source locations and estimated uncertainties (including estimates of systematic errors). We estimate that the overall positional uncertainty for all of these observations is 1.0 (1σ).

2.2. Optical and Near-Infrared Observations

The observations were carried out primarily with the Near-Infrared Camera (NIRC; Matthews & Soifer 1994) mounted on the 10 m Keck I telescope and were augmented with archival Hubble Space Telescope (HST) Wide Field Planetary Camera 2 (WFPC2) images. We also took auxiliary optical and infrared calibration images with the COSMIC imager and the PFIRCAM (Jarrett et al. 1994) infrared imager on the Palomar 5 m telescope (P200) and with the CCD optical imager on the Palomar 1.5 m telescope (P60CCD). A summary of the instruments, filters, exposures, and conditions is detailed in Table 2.

The optical data were reduced with the standard IRAF ccdred package. The images were bias subtracted, flat-fielded, registered, and co-added. The infrared data were reduced with custom IRAF software. The images were dark subtracted, flat-fielded, and corrected for bad pixels and cosmic rays. We then made object masks, which were used in a second round of flat-fielding to remove holes from the flats. The data were then registered, shifted, and co-added. The HST images were processed using the standard drizzling procedure (Fruhchter & Mutchler 1998).

The data from the P60CCD were used as the astrometric reference. We matched 36 nonsaturated stars to those from the USNO A2.0 Catalog (Monet 1998). Using the task cccmap, we computed a transformation solution, giving 0.2 residuals (all astrometric residuals are 1σ for each coordinate unless otherwise indicated). We then used this solution to fit stars on the COSMIC images. Using 37 stars, we again obtained 0.2 residuals.

We then used 15 stars on the COSMIC images to fit the HST image, getting 0.07 residuals. This solution was then used for the infrared images, fitting 10 stars on the NIRC images with 0.05 residuals. This gives 0.4 position uncertainties relative to the International Celestial Reference System, assuming the uncertainties intrinsic to the USNO A2.0 are 0.3 (for each axis; Monet 1998). We transferred this solution to the PFIRCAM images (0.3 residuals), but as this is only a photometric reference, the absolute position is not important.

For the optical photometry, we used V, R, and I observations of the standard fields1 Landolt 110, NGC 7790, and PG 1657 (Landolt 1992; Stetson 2000) carried out with the P60CCD. We fitted the observations over the whole night using air-mass corrections and first-order color terms and measured the R zero-point magnitude. We then examined

### Table 1

**Cas A X-Ray Observation Summary**

| Observation ID | Date       | CXO     | Exposure (ks) | R.A. (J2000)   | Decl. (J2000) |
|---------------|------------|---------|---------------|----------------|---------------|
| 214           | 1999 Aug 20| ACIS S3 | 6             | 23 23 27.94    | +58 48 42.4   |
| 1505          | 1999 Dec 20| HRC-I   | 50            | 23 23 27.88    | +58 48 42.1   |
| 1857          | 2000 Oct 5 | HRC-S   | 50            | 23 23 27.75    | +58 48 43.8   |
| Average       |            |         |               | 23 23 27.857   | +58 48 42.77  |
| Uncertainty   |            |         |               | 0.097          | 0.91          |

a Units of right ascension are hours, minutes, and seconds. Units of declination are degrees, arcminutes, and arcseconds. The individual source positions were calculated as centroids of the event distributions taken within a 1.0 radius circle about the location and iterated until the centroid location shifted by less than 0.1.

b Uncertainties are 1σ.

### Table 2

**Cas A Optical/Near-Infrared Observation Summary**

| Date          | Telescope/Instrument | Observer | Band | Exposure (s) | Conditions        |
|---------------|----------------------|----------|------|--------------|-------------------|
| 2000 Jan 22   | HST/WFPC2            | R. Fesen | F675W| 4000         | Slight cirrus     |
| 2000 Jun 27   | Keck I/NIRC          | S. Kulkarni | J  | 1600        | High cirrus      |
| 2000 Jul 4    | P200/COSMIC          | P. Mao   | R   | 1010        | Photometric       |
| 2000 Jul 5    | P200/COSMIC          | P. Mao   | R   | 1000        | Photometric       |
| 2000 Jul 24   | P60/P60CCD           | D. Kaplan | R  | 150         |                   |
| 2000 Sep 6    | P200/PFIRCAM         | D. Kaplan, J. Cordes | J  | 1680        |                   |
|               |                      |          | H   | 1680        |                   |
|               |                      |          | K   | 1120        |                   |

1 See http://cadcwww.dao.nrc.ca/cadcbin/wdb/astrocat/stetson/query/.
25 stars on the Cas A images common to both the P60CCD and COSMIC images and from this determined the zero point for the photometric night. From these data we also determined the limiting magnitude to be $R \sim 25$ mag.

For the infrared photometry, we used three observations of the faint United Kingdom Infrared Telescope standard stars FS 29 and FS 31 (Casali & Hawarden 1992) taken with the PFIRCAM. These observations were used to determine $J$, $H$, and $K_s$ zero points (we assumed the $K_s$ magnitudes were the same as the $K$ magnitudes, as the correction is typically $\lesssim 0.01$ mag: much smaller than our uncertainties; Persson et al. 1998). From these images we then found five stars common to the PFIRCAM and NIRC images and determined zero-point magnitudes for NIRC.

3. RESULTS

We searched for a counterpart to the XPS at position $\alpha(J2000) = 23^h23^m27^s.857$, $\delta(J2000) = +58^\circ 48' 42".77$, with 1sigma uncertainty (Table 1). See Figure 1 for the separate optical/infrared images. There was no source on COSMIC images, giving $R \gtrsim 25$ mag (3 $\sigma$ limit) for any possible counterpart (this agrees with the previous limit of $R \gtrsim 24.8$ mag and $I \gtrsim 23.5$ mag; van den Bergh & Pritchet 1986). On the NIRC, PFIRCAM, and HST images there was a source 1.7 away from the X-ray position at $\alpha(J2000) = 23^h23^m27^s.78$, $\delta(J2000) = +58^\circ 48' 41".2$ (±0'04 in each coordinate). Given the astrometric uncertainties, the overall position uncertainty is 1'1 in each axis, so this source is 1.5 $\sigma$ away from the nominal position. We label this source A and consider it as a potential candidate counterpart or companion to the X-ray source. The magnitudes of source A are $F675W = 26.7 \pm 0.2$ mag, $J = 21.4 \pm 0.3$ mag, $H \approx 20.5 \pm 0.8$ mag, and $K_s = 20.5 \pm 0.3$ mag. There are no other sources within the 2'3 radius 90% confidence circle.

4. ANALYSIS

Using the reddening and zero-point calibration data from Bessell, Castelli, & Plez (1998), we plot the spectral energy distribution for source A in Figure 2. This incorporates both the detections and limits.

To determine whether source A could be a star, we compared model stellar colors from Bessell et al. (1998) with our data. We fitted for three parameters: the visual extinction

![Figure 1](image-url)

FIG. 1.—Images of the region around the XPS: R band (COSMIC; upper left), J band (NIRC; upper right), H band (PFIRCAM; lower left), and K_s band (NIRC; lower right). A 2.3 radius circle (90% confidence) is drawn around the position of the XPS, and candidate source A is indicated. North is up and east is to the left. The images are $\approx 15'$ on each side.
$A_V$, the distance in kiloparsec $D_{\text{kpc}}$, and the stellar model (which includes the effective temperature $T_{\text{eff}}$, the surface gravity $g$, and the metallicity [Fe/H]). We assumed that the star would be a zero-age main-sequence star such that log $(R/R_\odot) = 0.7 \log (M/M_\odot) - 0.1$ (Habets & Heintze 1981) and used the bolometric corrections and reddening from Bessell et al. (1998) to find the expected magnitudes. To account for the upper limits in our fitting, we minimized a modified $\chi^2$ statistic such that

$$\chi^2 = \sum_i \left( \frac{m_i - m_{i, \text{mod}}}{\sigma_i} \right)^2$$

$$+ \sum_i \left\{ \frac{(m_{i, \text{mod}} - m_i)^2}{\sigma_i} \right\} \text{ if } m_{i, \text{mod}} \geq m_i;$$

$$0 \text{ otherwise}. \quad (1)$$

Here $i$ runs over the different filters, $m_i$ is the observed magnitude or limit for that filter, $m_{i, \text{mod}}$ is the model magnitude, and $\sigma_i$ is the uncertainty. The model uses standard Vega-based magnitudes but the HST data do not. Therefore we converted the HST magnitude to the Vega-based system using $R - F675W = -1.05 \text{ mag}$, appropriate for sources of this color.\(^2\) We do not incorporate model uncertainties into this statistic. Minimizing this $\chi^2$ seeks the best model that comes close in magnitude to the detections while remaining fainter than the nondetections. A full-fledged Bayesian analysis (e.g., Gregory & Loredo 1992; Cordes & Chernoff 1997) would be more accurate, but we wish only to demonstrate the plausibility of model fits, not assign specific probabilities to different models.

Given the number of variables, this fit is somewhat unconstrained. We restrict the extinction and distance to reasonable values ($0.5 \text{ mag} \lesssim A_V \lesssim 8 \text{ mag}, 0.5 \lesssim D_{\text{kpc}} \lesssim 5$) and fit for $\log g = 5.0$ (appropriate for late M stars; Habets & Heintze 1981). In addition, we require that $A_V$ roughly scale with $D$, excluding models that are very distant but have almost no extinction. We find that our detections and limits are entirely consistent with a cool (M6–8) Population II main-sequence star that is between the Earth and Cas A. Good fits are obtained for stars with $T_{\text{eff}} = 2600$–2800 K, [Fe/H] $= -2.0$, $D_{\text{kpc}} = 1.8$–2.0 kpc, and $A_V = 3.1$–3.2 mag (see Fig. 2 for examples). We do not give the $\chi^2$ value or formal confidence regions, as the $\chi^2$ in equation (1) is somewhat contrived and the models for stars this cool are not well determined (Bessell et al. 1998), but Figure 2 demonstrates the plausibility of the fits. That there is a star within 1.7 of the XPS is quite believable: the theoretical star-count models of Nakajima et al. (2000) give 1.5 $\times$ 10$^6$ stars deg$^{-2}$ of the appropriate colors with $J \lesssim 22.5 \text{ mag}$, leading to a false coincidence rate of 1.0. The best-fit star has $R = 0.2$, $M = 0.1 \ M_\odot$, and $L = 0.004 \ L_\odot$. Slightly deeper $I$-band observations should be able to verify the classification of source A.

As one might expect, there is a significant anticorrelation in the fits between values of $D_{\text{kpc}}$ and $A_V$, with $+0.25 \text{ kpc}$ and $+0.5 \text{ mag}$ variations giving reasonable fits, but the fits for the range of likely extinctions for Cas A (4–6 mag) at 3.4 kpc are definitely poor.

Assuming that source A is a late-type star, we examine whether it could be associated with the XPS, implying that both are in the foreground and that the XPS is not associated with Cas A. From Katsova & Cherepashchuk (2000) we see that for a star with $B - V \geq 1.8$ (from the model for source A), the X-ray luminosity is $L_{X, \text{star}}(0.1$–$2.4 \text{ keV}) \lesssim 10^{34} \text{ ergs s}^{-1}$ (also James et al. 2000; Marino, Micela, & Peres 2000), giving unabsorbed (denoted by superscript U) X-ray/infrared flux ratios of $f_{\nu}^U(v_j f_{\nu,k}^U) = 6 \times 10^{-4}$ and $f_{\nu}^U(v_K f_{\nu,K}^U) = 2 \times 10^{-2}$ for such a star. Converting the flux of the XPS to the ROSAT passband (using W3PIMMS$^3$), it has ratios of $f_{\nu}^U(v_j f_{\nu,k}^U) = 34$ and $f_{\nu}^U(v_K f_{\nu,K}^U) = 111$, which are drastically different. In addition, Pavlov et al. (2000) and Chakrabarty et al. (2001) did not observe any variability from the XPS, which is unlike late-type stars that can vary by factors of $\sim 10^2$ on small timescales (Marino et al. 2000). Source A therefore could not emit the X-rays observed from the XPS.

\(^2\) See http://www.stsci.edu/instruments/wfpc2/wfpc2_phot/wfpc2_cookbook.html.

\(^3\) See http://heasarc.gsfc.nasa.gov/tools/w3pimms.html.
We conclude that the XPS was not detected and added F675W $\gtrsim 27.3$ mag, $J \gtrsim 22.5$ mag, and $K_s \gtrsim 21.2$ mag (3 $\sigma$) along with a rough limit of $H \gtrsim 20$ mag to the previously mentioned limits.

5. DISCUSSION AND CONCLUSIONS

Based on a synthesis of CXO, ROSAT, and Einstein data, Pavlov et al. (2000) fitted the X-ray spectrum of the XPS. The absorbed flux is $8.2 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ in the 0.3–6.0 keV range (Pavlov et al. 2000). Power-law and pure blackbody models give good fits to the absorption-corrected data and are plotted as representative X-ray spectra in Figure 3. These results are similar to those from Chakrabarty et al. (2001). Pavlov et al. (2000) prefer the results of a H/He polar cap model with a cooler Fe surface, but all we wish to illustrate is that blackbody models are consistent with the optical limits while power-law models require a break between the X-ray and optical bands.

In Figure 3 we also plot the expected optical magnitudes of representative X-ray sources (an AXP and a tight X-ray binary) for comparison. These magnitudes are derived by taking the X-ray/optical flux ratios for these objects and scaling them to the X-ray flux of the XPS. We can likely reject sources such as 4U 1626–67 (Chakrabarty 1998) from consideration, but the extrapolation of the AXP 4U 0142+61 (Hulleman, van Kerkwijk, & Kulkarni 2000) is consistent with the current limits.

Giving the presumed distance and reddening, our limits translate to $M_R \gtrsim 8.2$ mag, $M_{F675W} \gtrsim 10.7$ mag, $M_J \gtrsim 8.5$ mag, $M_{K_s} \gtrsim 6.5$ mag, and $M_{K_s} \gtrsim 8.0$ mag. We find the observed X-ray/infrared flux ratios to be $f_X/(F_{F675W}) \gtrsim 2872$, $f_X/(v_J f_{J}) \gtrsim 212$, and $f_X/(v_{K_s} f_{K_s}) \gtrsim 280$ (the X-ray flux is in the 0.3–6.0 keV band). If we correct for interstellar absorption, we find unabsorbed ratios of $f_X/(F_{F675W}) \gtrsim 231$, $f_X/(v_J f_{J}) \gtrsim 166$, and $f_X/(v_{K_s} f_{K_s}) \gtrsim 467$ using the X-ray flux from Chakrabarty et al. (2001). These flux ratios, larger than those inferred previously, tighten constraints on the identity of the XPS (e.g., Umeda et al. 2000; Pavlov et al. 2000).

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