THE ENIGMATIC X-RAY POINT SOURCES AT THE CENTRAL STARS OF NGC 6543 AND NGC 7293

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ABSTRACT

Recent Chandra ACIS-S observations have detected a point source at the central star of NGC 6543 and confirmed the point-source nature of the hard X-ray emission from NGC 7293. The X-ray spectra of both sources peak between 0.5 and 1.0 keV and show line features indicating a thin plasma at temperatures of a few times 10^6 K. Their X-ray luminosities are 10^30 and 3 × 10^30 ergs s^-1, respectively. We have considered four different mechanisms to explain the nature of these sources. The X-ray emission from the central star of NGC 6543 may originate from the coronal activity of an undetected companion star or from shocks in its fast stellar wind, while the hard X-ray emission from NGC 7293 might be ascribed to an undetected dMe companion. Follow-up observations are needed to determine the existence and nature of these stellar companions.

Subject headings: planetary nebulae: general — planetary nebulae: individual (NGC 6543, NGC 7293) — stars: AGB and post-AGB — X-rays: stars

1. INTRODUCTION

Central stars of planetary nebulae (PNs) are expected to emit soft X-rays if their effective temperatures are greater than 100,000 K. Indeed, such X-ray sources have been detected by Einstein, EXOSAT, and ROSAT, and the X-ray photons detected have energies well below 0.5 keV (Hoare et al. 1995; Guerrero, Chu, & Gruendl 2000). In addition to the soft X-ray emission from the photosphere, ROSAT observations of the central stars of LoTr 5 and NGC 7293 (also known as the Helix Nebula) show a harder X-ray component peaking between 0.5 and 1.0 keV (Leahy, Zhang, & Kwok 1994; Guerrero, Chu, & Gruendl 2000). The central star of LoTr 5 is a known binary (Feibelman & Kaler 1983), and the coronal activity of its G5 III companion may be responsible for the hard X-ray emission (Hoare et al. 1995; Jasniwecz et al. 1996). The central star of NGC 7293, on the other hand, is not a known binary (Ciardullo et al. 1999).

It has been suggested that the hard X-ray emission from NGC 7293 originates from the interaction between the fast stellar wind and the ambient nebular material (Leahy, Zhang, & Kwok 1994; Leahy et al. 1996). If this is true, the X-ray emission from NGC 7293 should be spatially extended, similar to that observed in NGC 6543 (Chu et al. 2001). We have obtained Chandra observations of NGC 7293 and find that this source remains unresolved by Chandra’s high resolution.

We have also obtained Chandra observations of NGC 6543 (the Cat’s Eye Nebula) and find that its central star emits X-rays, too (Chu et al. 2001). The X-ray spectrum of this source peaks at above 0.5 keV; thus, NGC 6543 joins NGC 7293 as a host of an enigmatic point X-ray source. This Letter reports our Chandra observations of the point sources in NGC 6543 and NGC 7293. The observations are described in § 2, the properties of the X-ray emission are presented in § 3, the possible origins of these X-ray sources are discussed in § 4, and the conclusions are summarized in § 5.

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2. OBSERVATIONS

NGC 6543 and NGC 7293 were observed with the Advanced CCD Imaging Spectrometer (ACIS) on board the Chandra X-Ray Observatory on 2000 May 10–11 and 1999 November 17–18 for total exposure times of 46.0 and 47.7 ks, respectively. The nebular centers were placed on the back-illuminated CCD chip S3, the nominal aim point for the ACIS-S array. The instrumental FWHM of the ACIS-S array is 0.7–0.8 at ≤1 keV (A. Ware & B. R. McNamara 1999). The energy resolution, E/ΔE, is ~4.3 at 0.5 keV and ~9 at 1.0 keV.

We received level 1 and level 2 processed data from the Chandra Data Center. The data reduction and analysis were performed using the Chandra X-Ray Center software CIAO v1.1.5 and HEASARC FTOOLS and XSPEC v11.0.1 routines (Arnaud 1996). No background “flares” affected the observations, and no time intervals needed to be removed.

3. PROPERTIES OF THE X-RAY EMISSION

3.1. Identification of Point Sources

The Chandra observations of NGC 6543 detected 1950 ± 50 counts, of which ~100 counts originated at a pointlike source and the rest corresponded to diffuse emission (Chu et al. 2001). The observations of NGC 7293 detected 2100 ± 50 counts, all from a pointlike source. The Chandra coordinates of both pointlike sources are within 1" of the coordinates of the central stars derived from the Digitized Sky Survey. To further examine their relative positions, we have matched field stellar sources detected in the ACIS observations with bright stars in the Digitized Sky Survey. When the field sources are aligned, we find that the agreement in position between the pointlike X-ray source and the central star is better than 0.5" for both NGC 6543 and NGC 7293. Therefore, we conclude that these pointlike X-ray sources are coincident with the central stars.

It is difficult to assess whether the pointlike X-ray source at NGC 6543’s central star is truly unresolved because only...
~100 counts are detected and it is superposed on bright diffuse X-ray emission. This pointlike X-ray source cannot be a local peak of the diffuse emission because they have different spectral shapes (see § 3.2); thus, it is likely a true point source associated with the central star.

The ACIS observations of NGC 7293 have detected adequate counts to allow an accurate comparison between the surface brightness profile of the pointlike source and the instrumental point-spread function. The FWHM of the surface brightness profile of the X-ray source in NGC 7293 is 0.8', comparable to the instrumental FWHM. Therefore, the X-ray source in NGC 7293 is unresolved and is a true “point” source.

3.2. Spectral Properties of NGC 6543

The spectrum of the point source at the central star of NGC 6543 was extracted using a round source aperture of 1.7’ radius and a concentric annular background aperture of radii from 1.5’ to 2.5’. The background region was selected to be representative of the diffuse emission in the central region of the nebula while avoiding the bright emission along the rim (see image of diffuse emission in Chu et al. 2001). The background-subtracted spectrum of the central star of NGC 6543 is presented in Figure 1. It shows emission-line features at 0.45–0.7 and ~0.9 keV and much fainter emission at higher energies in the range of 1.0–2.0 keV. The feature between 0.45 and 0.7 keV is brighter and wider and corresponds to the He-like triplet of O viii at ~0.57 keV and the H-like Lyα line of O viii at 0.65 keV. The feature at ~0.9 keV is fainter and may be attributed to the He-like triplet of Ne ix at ~0.92 keV. The spectrum at 1.0–2.0 keV has too few counts for us to determine whether it is line or continuum emission.

The line features in the spectrum of the central star of NGC 6543 are consistent with thermal plasma emission. The number of counts is too small for reliable spectral fits; therefore, we will limit our analysis to the comparison of the observed spectral shape with thermal plasma emission models convolved with an absorption column and the instrumental response. For this, we used the MEKAL model in the XSPEC software package (Mewe, Lemen, & van den Oord 1986; Kaastra 1992; Liedahl et al. 1992) and an absorption column density, $N_H \approx 8 \times 10^{20} \text{ cm}^{-2}$, determined from the ACIS-S spectral fits of the diffuse emission from NGC 6543 (Chu et al. 2001). Solar abundances are adopted for both the emitting plasma and absorbing material.

Several models have been considered to simulate the observed spectrum (see Fig. 1). For models with one temperature component, the relative intensity of the emission features at 0.45–0.7 and ~0.9 keV can be simulated only if the abundance of Ne is greatly enhanced from the solar value; the best model has a plasma temperature of $T \sim 2 \times 10^6$ K. For models with two temperature components, no anomalous Ne abundances are needed, and the observed spectral shape can be described by a MEKAL model with $T_1 \sim 2 \times 10^6$ K and $T_2 \sim 9 \times 10^6$ K. The unabsorbed X-ray luminosity, calculated from either the best one- or two-temperature model, is ~$10^{30}$ ergs s$^{-1}$ in the 0.3–2.0 keV band, for a distance of 1 kpc (Reed et al. 1999).

3.3. Spectral Properties of NGC 7293

The spectrum of the point source at the central star of NGC 7293 was extracted using a round source aperture of 1.5’ radius and a concentric annular background aperture of radii from 10” to 25”. The background-subtracted spectrum (Fig. 2, left) shows emission from 0.3 to 2.0 keV with numerous line features (note that ACIS is not sensitive to the soft X-ray component detected by ROSAT). The emission in the energy range of 0.5–0.7 keV consists of the O vii lines at 0.57 keV and the O viii line at 0.65 keV. Note that the relative intensities of the O vii and O viii lines of NGC 7293 are reversed from those of NGC 6543, indicating a higher plasma temperature for the source in NGC 7293. The peak emission, in the energy range of 0.7–0.85 keV, corresponds to the Fe xvii lines at ~0.73 and ~0.83 keV. The secondary peak, at 0.9 keV, is attributed to Ne ix lines at ~0.92 keV. The Ne x line and Fe L blend at 1.02 and 1.1 keV, respectively, can also be identified in the spectrum. In the energy range above 1.1 keV, the emission drops off steadily; the low signal-to-noise ratio prevents us from identifying the emission lines unambiguously.

The spectrum of the point source in NGC 7293 has been fitted using the MEKAL model. The best fit (see Fig. 2, left) has $T \approx 7.4 \times 10^4$ K and $N_H \approx 4 \times 10^{20} \text{ cm}^{-2}$. The goodness of the fit can be assessed from the reduced $\chi^2$ plotted as a function of $N_H$ and $kT$ (Fig. 2, right). The 99% confidence contour spans $N_H = (2.8 \pm 0.2) \times 10^{20} \text{ cm}^{-2}$ and $T = (7 \pm 1.1) \times 10^4$ K (or $kT = 0.60 \pm 0.07$ keV). This absorption column density is, within the error limit, consistent with that determined from ROSAT Position Sensitive Proportional Counter (PSPC) observations, $N_H = (2.8 \pm 0.2) \times 10^{20} \text{ cm}^{-2}$ (Leahy et al. 1996). The unabsorbed X-ray luminosity is ~$3 \times 10^{30}$ ergs s$^{-1}$ in the 0.3–2.0 keV band, for a distance of 210 pc (Harris et al. 1997).
3.4. Temporal Brightness Variation of the Point Source in NGC 7293

The 47.7 ks observations of NGC 7293 were made in two intervals, 36.7 and 11.0 ks, separated by a 22.6 ks gap. We have examined the temporal variation of the brightness of the source over this time span by dividing the observations into nine roughly equal time bins. The count rate is plotted against time in Figure 3. The average ACIS count rate of this source is consistent with that expected from the ROSAT PSPC observations of the hard component on 1992 May 12–13. The ACIS count rates from the seven bins in the first time interval show 1σ level variations. The count rates from the final two bins, on the other hand, show a noticeable decrease from the first time interval. Both the peak-to-peak variation and the difference between the mean of the first seven bins and the mean of the last two bins have greater than 3σ significance. These results provide the first detection of short-term variability of the X-ray source in NGC 7293.

4. POSSIBLE ORIGINS OF THE X-RAY EMISSION

4.1. Wind-Nebula Interaction

It has been suggested that the hard X-ray emission from the central star of NGC 7293 originates from the interaction between its stellar wind and the surrounding nebula (Leahy et al. 1996), because central stars of PNs often exhibit energetic fast stellar winds (Patriarchi & Perinotto 1991). Such interacting-wind models (Kwok, Purton, & Fitzgerald 1978) show that the PN interior is filled with hot gas (the shocked fast wind), and the X-ray emission from the hot gas will peak near the inner wall of the PN shell, where the density of the hot gas is raised by the mass evaporation across the interface (e.g., Mellema & Frank 1995; Zhekov & Perinotto 1998). Diffuse X-ray emission compatible with this picture has been detected by Chandra in the interiors of BD+30°3639, NGC 6543, and NGC 7027 (Kastner et al. 2000; Kastner, Vrtilek, & Soker 2001; Chu et al. 2001). In all cases, the observed spectra are consistent with a thin plasma at a few times 10^6 K.

The ACIS spectra of the central stars of NGC 6543 and NGC 7293 are qualitatively similar to those expected in the wind-nebula interaction models, but the X-ray emission is confined to the vicinity of the central star as opposed to peaking near the inner wall of the PN shell. Furthermore, the central star of NGC 7293 currently does not seem to possess a measurable fast stellar wind (Cerruti-Sola & Perinotto 1985). It is unlikely that the X-ray emission from these point sources originates from wind-nebula interaction.

4.2. Shocks in the Stellar Wind

Shocks in fast stellar winds are believed to be responsible for the X-ray emission from massive O and B stars (Cassinelli et al. 1994). X-ray observations of O and B stars show that their spectra are consistent with thin plasma emission at a few times 10^6 K and that $L_X/L_{bol} = 10^{-7}$ (Chlebowski, Harnden, & Sciortino 1989). While the central star of NGC 7293 does not have a measurable fast wind, the central star of NGC 6543 does exhibit a strong fast stellar wind (Patriarchi & Perinotto 1991). With an $L_{bol}$ of $\sim 10^{37}$ ergs s$^{-1}$ (Perinotto, Cerutti-Sola, & Lamers 1989), the $L_X/L_{bol}$ of the central star of NGC 6543 is within the range expected for sources with wind shocks. Therefore, the X-ray emission from the central star of NGC 6543 may originate from shocks in its fast stellar wind.

4.3. Accretion of Material from a Close Binary Companion

A compact object with a close binary companion may form an accretion disk and emit X-rays (e.g., the low- and high-mass
X-ray binaries). The maximum temperature that can be achieved in the accretion disk material scales with $M^{1/4}R^{3/4}$, where $M$ and $R$ are the mass and radius of the accreting star and $M$ is the mass transfer rate in the binary system (Pringle 1981). For a radius of 0.01 $R_\odot$ and a mass of 0.6 $M_\odot$, typical for PN central stars, the maximum temperature achievable in the accretion disk is well below $10^9$ K for a mass transfer rate of less than $10^{-7} M_\odot$ yr$^{-1}$. No X-ray emission is expected from such cold accretion disks.

Alternatively, the accreted mass may fall onto the surface of a compact object directly and emit X-rays. For white dwarfs, the infall velocity is so high that a shock develops above the star and the infalling gas is shock-heated to $10^8$ K and emits X-rays, e.g., dwarf novae, polars, and intermediate polars (Sion 1999; Cropper 1990; Patterson 1994). The X-ray spectra of the central stars of NGC 6543 and NGC 7293 are clearly too soft; furthermore, the optical brightness does not show the large variability observed in white dwarfs that accrete mass at high rates (A. Landolt 2000, private communication). Accretion of material from a close binary companion cannot contribute to the observed X-ray emission from these point sources.

### 4.4. Coronal Activity of the Central Star or a Dwarf Companion

X-ray emission from stellar coronae has similar spectral properties to the X-ray emission from the central stars of NGC 6543 and NGC 7293. Coronal activity is powered by convection and differential rotation in the envelopes of late-type F–K stars and dMe flare stars (dwarf M stars with emission lines). Evolved stars, going from the end of the asymptotic giant branch phase to the proto-PN stage, may also have convective envelopes (Blackman et al. 2001). As a star evolves into a white dwarf, however, the ionization of H and He in its photosphere increases, and the convection and coronal activity will cease at $T_{\text{eff}}>30,000$ K (Böhm & Cassinelli 1971). Neither NGC 6543 nor NGC 7293 are proto-PNs. In fact, the central star of NGC 6543 ($T_{\text{eff}}=30,000$ K) is already a 100,000 K hot white dwarf. Therefore, it is unlikely that they have coronal activity.

It is possible that the central stars of NGC 6543 and NGC 7293 have binary companions with coronal activity. The luminous central star of NGC 6543 ($T_{\text{eff}}=5600$ K; Perinotto et al. 1989) can easily hide an F–M dwarf companion. An undetected companion has been suggested to explain the precessing collimated outflows in NGC 6543 (Miranda & Solf 1992; Harrington & Borkowski 1994). A careful search is needed to determine whether a binary companion exists.

Observations of the central star of NGC 7293 have shown that no companion star with spectral type earlier than M5 is present (Ciardullo et al. 1999). On the other hand, the temporal variability of NGC 7293 is similar to those observed from dMe flare stars in a quiescent state (White 1996). Furthermore, the broad ($\sim300$ km s$^{-1}$) variable Hα emission from the central star of NGC 7293 recently detected by Gruendl et al. (2001) is similar to that seen during flares of dMe stars. A dMe companion is currently the most plausible explanation for the X-ray emission from NGC 7293.

### 5. Conclusions

Using Chandra ACIS-S observations, we have discovered a point source at the central star of NGC 6543 and confirmed the point-source nature of the hard X-ray emission from NGC 7293. The spectra show line features indicating a thin plasma at temperatures a few times $10^7$ K. The luminosities of these sources are $10^{30}$ and $3\times10^{30}$ ergs s$^{-1}$, respectively. The central point source in NGC 6543 is detected because of the unprecedented resolution and sensitivity of Chandra, and the central star of NGC 7293 is detected because it is one of the nearest PNs. We conclude that the X-ray emission from the central star of NGC 6543 may be ascribed to coronal activity of a late-type companion star or to shocks in its stellar wind; the X-ray emission from the central star of NGC 7293 may originate from a companion dMe star. Follow-up observations are needed to determine the existence and natures of these stellar companions.

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ERRATUM

In the Letter “The Enigmatic X-Ray Point Sources at the Central Stars of NGC 6543 and NGC 7293” by Martín A. Guerrero, You-Hua Chu, Robert A. Gruendl, Rosa M. Williams, and James B. Kaler (ApJ, 553, L55 [2001]), the reference to the companion paper by Chu et al. (in the same issue, 2001 May 20) reads “ApJ, L000” and has no volume number. It should read “ApJ, 553, L69.”