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THE ROSAT X-RAY SPECTRUM OF THE HELIX NEBULA

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RESUMEN

Hemos descubierto por primera vez, la existencia de dos componentes de temperatura en la emisión de rayos X de una nebulosa planetaria. El espectro observado ROSAT PSPC de la Nebulosa de la Hélice exhibe un fuerte pico cercano a 0.12 KeV y un pico secundario cercano a 0.8 keV. El mejor ajuste del modelo resulta en una temperatura de $T_1 = 14 \times 10^5$ K para la componente de baja energía y una temperatura de $T_2 = 8.7 \times 10^6$ K para la componente de alta energía, con una densidad en la columna de hidrógeno de $N_H = 1.41 \times 10^{20}$ cm^{-2}. La componente de baja energía puede atribuirse a la fotosfera de la estrella central. La componente de alta energía puede ser ocasionada por una corona estelar. Una explicación alterna es que esta componente caliente se debe al plasma en una burbuja caliente predicha por el modelo de viento en interacción. El límite inferior de la densidad electrónica en el plasma caliente es cercano a 10 cm^{-3}.

ABSTRACT

We have for the first time discovered the existence of two temperature components in the X-ray emission from planetary nebulae. The observed ROSAT PSPC spectrum of the Helix Nebula exhibits a strong peak at about 0.12 keV and a secondary peak at about 0.8 keV. The best model fit results in a temperature of $T_1 = 1.4 \times 10^5$ K for the low-energy component, and a temperature $T_2 = 8.7 \times 10^6$ K for the high-energy component, at hydrogen column density $N_H = 1.41 \times 10^{20}$ cm^{-2}. The low-energy component can be attributed to the photosphere of the central star. The high-energy component may be caused by a stellar corona. An alternative explanation is that this hot component is due to plasma in a hot bubble predicted by the interacting wind model. A lower limit of the electron density in the hot plasma is about 10 cm^{-3}.

Key words: **PLANETARY NEBULAE: INDIVIDUAL (NGC 7293) — X-RAYS: INTERSTELLAR**

1. INTRODUCTION

NGC 7293 [22^h 26^m 55^s, -20° $50'$ $15''$(1950.0)] is a large and nearby planetary nebula (PN), also known as the Helix Nebula. It has a diameter of about $10'$ (Pottasch 1984) and extinction of $c = 0.04$ (Kaler 1983). The hydrogen and HeII Zanstra temperatures are estimated at 110,000 and 113,000 K (Pottasch 1984), while the spectroscopic effective temperature of the central star is about 90,000 K obtained by model fitting to the absorption line profiles (Mendez et al. 1988). Zhang & Kwok (1993) have developed a new method to determine the stellar core mass and luminosity (L_*) for a sample of 303 planetary nebula central stars (PNCS), using distance-independent parameters from radio and infrared measurements. They have obtained that the core mass and luminosity of this PNCS are about $0.605 M_\odot$ and $100 L_\odot$. A distance of the Helix Nebula is determined by Zhang (1993) as 160 pc. Throughout this paper we will adopt the distance of 160 pc.

Early detection of X-ray emission was made by the Einstein Observatory (Tarafdar & Apparao 1988) and the EXOSAT satellite (Apparao & Tarafdar 1989) for about 11 PN. Apparao & Tarafdar (1989) found that the Helix Nebula was observed to have an unabsorbed flux of $(6.9 \pm 1.9)\times10^{-13}$ $ergs\ cm^{-2}\ s^{-1}$ by the EXOSAT. They estimated that the X-ray luminosity (L_x) is about 1.1×10^{30} $ergs\ s^{-1}$ at a distance of 116 pc. They suspected that this relatively low X-ray luminosity of the Helix Nebula was due to the underestimated interstellar extinction. The X-ray emission from the above PNs was attributed to the photosphere of the PNCS by the above authors. They pointed out that the X-rays from the PNCS would be visible when the nebula disperses or when the heavy elements in the PNCS atmosphere settle down.

Kreysing et al. (1993) have reported detection of X-ray emission from 6 PN using ROSAT All Sky Survey, with an X-ray temperature of a few times 10^5 to 10^6 K. Five of the six PN are claimed to have extended X-ray emission. Kwitter et al. (1993) have obtained ROSAT Position Sensitive Proportional Counter (PSPC) data of NGC 6853. They find that the emission from NGC 6853 is not extended at all, in contradiction to Kreysing et al.

The nature of the X-ray emission cannot be fully understood through those early observations, since it was impossible to obtain X-ray spectra of high quality from the previous X-ray satellites. Pointed observations with the ROSAT PSPC are important for us to be able to obtain enough counts and X-ray spectra of high quality. In this paper, we report new observations of the Helix Nebula, using the ROSAT PSPC.

2. OBSERVATIONS

The Helix Nebula was observed by the ROSAT PSPC counter during the third period of Pointed Observations (AO3). The energy response of the ROSAT X-ray telescope extends from 0.1 to 2 keV. The PSPC at the focal plane provides an angular resolution of about $30''$ and a field of view of 2°. The spectral resolution is 40% (FWHM) at 1 keV. The Helix Nebula was observed at the on-axis position for a total exposure time of 9.26 ksec. We obtained about 345 net counts for this source.

The background subtracted X-ray spectrum of the Helix Nebula is extracted by binning the X-ray photon events into the ROSAT PSPC energy bins. The resulting observed spectrum is shown in Figure 1. The data points of net counts per channel in each bin are plotted against the energy. One sigma error bars are also shown. The dashed line is a model fit described below. The spectrum shows that the bulk of the photons are in the energy range from 0.1 to 0.5 keV with a strong peak at about 0.12 keV, where the low energy cut-off is determined by the detector. It is clear, however, that there is a secondary peak at about 0.8 keV; non-negligible net emission of hard photons is seen in the energy range from about 0.5 to 3 keV.

3. RESULTS

The Helix ROSAT X-ray spectrum was fitted by several different spectral models. None of the single-component models can fit the observed spectrum. A Two-temperature Reymond-Smith (hereafter 2-T RS) model gives a satisfactory fit to the observed spectrum. The model results are such that the best fit requires a temperature of $kT_1 = (0.015 \pm 0.005)$ keV ($T_1 = 1.4\times10^5$ K) for the low-energy component, and a temperature $kT_2 = (0.8\pm0.15)$ keV ($T_2 = 8.7\times10^6$ K) for the high-energy component, at the hydrogen column density $logN_H = (20.15\pm0.7)$ cm^{-2}, where one σ error is indicated at a 68 % confidence level. The best model spectrum is illustrated in Figure 1 as a dashed line. The emission measures for the 2-T RS fit are $log(EM) = 14.74$ and 9.34 in units of cm^{-5} for the low- and high-energy components, respectively. The χ^2_{min} is 46.0 for the best fit.

The total observed X-ray fluxes are 1.87×10^{-13} and 7.66×10^{-14} and the unabsorbed X-ray fluxes are 4.36×10^{-11} and 9.26×10^{-14} $ergs\ cm^{-2}\ s^{-1}$, respectively for the low-energy and high-energy components. The unabsorbed X-ray luminosity in the range from 0.1 to 1 keV is therefore about 1.33×10^{33} $ergs\ s^{-1}$ at the distance of 160 pc. Uncertainties in the estimated unabsorbed fluxes and luminosity come mainly from the uncertainties in the estimate of the interstellar extinction and in the model fitting parameters. The galactic hydrogen column density obtained from the best model fit of about 1.41×10^{20} cm^{-2} implies a color excess of $E(B-V) = 0.024$, or, $c = 0.03$, using the conversion factor of $N_H = 5.8\times10^{21}$ $E(B-V)$ cm^{-2} mag^{-1}. This result of $c = 0.03$ is in good agreement with the value of $c = 0.04$ derived by Kaler (1983), using the methods of the Balmer decrement, the comparison of the radio continuum flux densities, and the colors of the central star. The X-ray luminosity of only 1.1×10^{30} $ergs\ s^{-1}$ obtained by Apparao & Tarafdar is much too low, as was suspected due to the zero interstellar extinction they adopted.

We have also analyzed the spatial distribution separately for the low- (channels 7-40) and high-energy (channels 41-240) photons. We divide the source into a set of annuli with the width of $15''$ and plot the spatial profile of counts per pixel as a function of radius from the peak of the source (not shown). The 50 % encircled energy is within about 30″ for the low-energy component, and 15″ for the high-energy component. The on-axis radius of the circle containing 50 % of the source counts is about 30″ and 15″ respectively for soft and hard photons (Hasinger et al. 1992). Neither of the two components is found to be resolved by the ROSAT PSPC, compared to the point spread function of Hasinger et al. (1992).

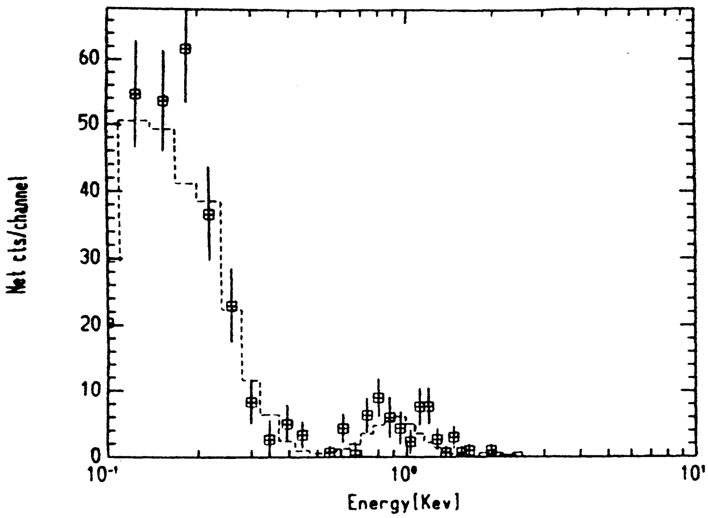

Fig. 1. — The ROSAT PSPC spectrum of NGC 7293.

4. DISCUSSION

4.1. Low-energy component

The low-energy component may be attributed to the photosphere of the PNCS, as the helium Zanstra temperature of $T_Z(HeII) = 1.13 \times 10^5\ K$ (Pottasch 1984) is consistent with our value of T_1. Furthermore, this low-energy component is not spatially resolved by the ROSAT PSPC, indicating the intrinsic size of the source may be small. Suppose that the central star of the Helix Nebula radiates like a blackbody, the angular radius of the star may be estimated from the observed X-ray flux as

$$\theta = \sqrt{\frac{F_x}{\pi \int_{\nu_1}^{\nu_2} B_\nu(T_*) d\nu}} \qquad (1)$$

where T_* is the central star temperature, F_x is the observed X-ray flux corrected for extinction over the frequency range from ν_1 to ν_2, and B_ν the Planck function. If we take T_* as the helium Zanstra temperature of $1.13 \times 10^5\ K$, and the unabsorbed X-ray flux of the low-energy component at the earth in Section 3, we find from Equation (1) that the angular radius of the the low-energy X-ray emitting region is about 1.6×10^{-7} *arcsec*. This is not in conflict with the angular radius of the central star of 7.6×10^{-7} *arcsec*, estimated from the total stellar luminosity $L_* = 100 L_\odot$ and the temperature of the star of $1.13 \times 10^5\ K$. We conclude that the low-energy component of the X-ray emission is due to the stellar photosphere.

4.2. The high-energy component

The X-ray luminosities, L_x, of *NGC* 246/1360/4361/1535/6853 and *A*36 derived from the EXOSAT results (Apparao & Tarafdar 1989) are found to be in excess of the would-be X-ray luminosity implied by the X-ray Zanstra temperatures derived by the same authors (L_x can reach a few percent of L_*). This may suggest that in addition to the stellar photosphere, contribution from an X-ray source related to a fast wind from the PNCS, a corona, and/or the PNCS being a binary system, where mass transfer plays a role, is needed. This "excess" X-ray emission would likely come from a hot plasma.

Our detection of the high-energy component in the X-ray spectrum of the Helix Nebula clearly demonstrates the presence of a very hot plasma. It is possible that the central star might have developed a corona, which may be related to a strong convection in the star. An alternative explanation is the hot bubble predicted by the interacting wind model (Kwok et al. 1978). Both can generate temperatures above one million K. One way to distinguish between the two possibilities is to spatially resolve the hot component. The hot bubble model predicts a spatial extent much larger than the stellar radius (Kwok et al. 1978), while the corona has a size which is comparable with the stellar photosphere.

The electron density of the high-energy component X-ray emitting region can be estimated from the emission measure obtained by the model fitting and the distance of the nebula, if the angular size is known. From our ROSAT PSPC data, the high-energy component is not resolved, so only the upper limit of the angular radius can be estimated as about $15''$. This will lead to a lower limit for the electron density in the emitting region.

$$n_e = \sqrt{\frac{3(EM)}{(n_p/n_e) f \theta_r^3 d}} \qquad (2)$$

where EM is the emission measure, the proton to electron density ratio (n_p/n_e) can be estimated as 0.84 for a helium to hydrogen abundance ratio of 0.11, f is the filling factor, θ_r is the angular radius of the emitting region, and d is the distance. Assuming the filling factor $f = 0.6$, and the upper limit of the angular radius $\theta_r = 15''$, we obtain the lower limit of the electron density is 10 cm^{-3}. The true electron density in the region of the hot plasma can only be obtained accurately when the region is resolved. In this respect, high spatial resolution imaging of X-ray emitting regions from PNs is highly desirable.

5. SUMMARY

The X-ray spectrum was obtained during pointed observations of the Helix Nebula by the ROSAT PSPC counter. For the first time we have discovered the presence of two temperature components in the X-ray spectra of a planetary nebulae. A single-temperature spectral model cannot account for the observed spectrum of the Helix Nebula. A model consisting of a component with a temperature of $140,000\ K$ plus another with a temperature of $8,700,000\ K$ is needed to give the best fit. We find that the nature of the low-temperature component is adequately attributable due to the photosphere of the central star, because the temperature obtained from the X-ray spectrum is consistent with the helium Zanstra temperature of the central star, and because the angular radius of the emitting region is on the same order of magnitude as that of the central star, based on the bolometric luminosity, the temperature, and the distance of the central star. We propose that the X-ray emission of the high-temperature component originates from either a stellar corona, or a hot bubble produced by the interaction between the fast wind from the central star and the slow wind of the remnant of the progenitor star. We estimate that the electron density must have a lower limit of 10 cm^{-3}.

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