DIFFUSE X-RAY EMISSION FROM THE DUMBBELL NEBULA?

YOU-HUA CHU
Department of Astronomy, University of Illinois, Urbana, Illinois 61801
Electronic mail: chu@dorado.astro.uiuc.edu

KAREN B. KWITTER
Department of Astronomy, Williams College, Williamstown, Massachusetts 01267
Electronic mail: kkwitter@williams.edu

JAMES B. KALER
Department of Astronomy, University of Illinois, Urbana, Illinois 61801
Electronic mail: kaler@sirius.astro.uiuc.edu

Received 1993 January 27; revised 1993 April 12

ABSTRACT

We have analyzed *ROSAT* Position Sensitive Proportional Counter pointed observations of the Dumbbell Nebula and find that the previously reported "extended" x-ray emission is an instrumental electronic ghost image at the softest energy band. At slightly higher energy bands, the image of the Dumbbell is not very different from that of the white dwarf HZ43. We conclude that the x-ray emission of the Dumbbell Nebula comes from its central star. A blackbody model is fitted to the spectrum and the best-fit temperature of $\leqslant 136\,000 \pm 10\,000$ K is in excellent agreement with the Zanstra temperatures.

1. INTRODUCTION

Planetary nebulae (PNe) are formed by mass loss from stars with initial masses $\leqslant 8 \mathcal{M}_{\odot}$. Since fast stellar winds with terminal velocities of 600 to 3500 km s^{-1} have been detected in a large faction of PN nuclei (Patriarchi & Perinotto 1991), and since the progenitors of PNe have lost mass via slow winds at the red giant phase and via "superwinds" on the asymptotic giant branch (AGB) at 10–25 km s^{-1} (Knapp 1989), the fast stellar winds inevitably will catch up and interact with the previous slow winds (Kwok *et al.* 1978). This wind-interaction mechanism provides the bases for the popular two-wind or three-wind models of PN formation (Kwok 1983; Kahn 1989; Frank *et al.* 1990; Icke 1991).

In hydrodynamical model calculations of interacting winds, the fast stellar wind is shocked into a hot plasma at a few times 10^6 K, from which soft x-ray emission is expected. This situation is similar to that of bubbles blown by massive OB or Wolf–Rayet stars (Weaver *et al.* 1977), and diffuse x-ray emission has indeed been detected in NGC 6888 (Bochkarev 1988) and the Rosette Nebula (Leahy 1985) by the Einstein Observatory. However, *Einstein* and EXOSAT observations of PNe have detected x-rays that are identified as purely stellar in origin (Tarafdar & Apparao 1988; Apparao & Tarafdar 1989).

The high sensitivity of the Position Sensitive Proportional Counter (PSPC) of the *ROSAT* satellite has generated renewed interest and hope in detecting diffuse soft x-rays expected from the shocked fast winds in PNe. There is no sure and simple way to select targets because of the uncertainties in the physical parameters of PNe and in model calculations. We chose our target by examining all *Einstein* IPC images of PNe and selecting the one that showed some hint of extended emission. The Dumbbell Nebula (NGC 6853) is thus chosen; it is also chosen for its large angular size ($\sim 7'$ in diameter), its nearness ($d \leqslant 250$ pc) and its low redenning ($A_V \sim 0.1$–0.45 mag) (Cahn *et al.* 1992; Kaler 1983).

Before we received the data of our pointed observations of the Dumbbell, Kreysing *et al.* (1992) had already reported diffuse x-ray emission in this nebula using the *ROSAT All Sky Survey*. However, after careful analysis of our data, we conclude that the alleged "extended" x-ray emission is not real. This paper reports our investigation of x-ray emission from the Dumbbell Nebula.

2. OBSERVATIONS AND RESULTS

The Dumbbell Nebula was observed with the *ROSAT* PSPC in the open mode (without boron filter), during four intervals between April 29 and May 1 in 1992 for a total exposure of 5.32 ks. The observation ID is 200568. Since these observations were carried out by PSPC2 at the low gain state, the pulse-height invariant, PI, channels 10 and below were corrupted. We should use only data in PI channels above 10, or above 0.1 keV. The data were analyzed using PROS.

Figure 1 shows the x-ray image of the Dumbbell compressed in energy above 0.1 keV. At a first glance, the x-ray source in the Dumbbell appears to consist of a subarcmin core and a faint halo within a $2'$ radius. The angular extent is sufficiently small that the cosmic and noncosmic backgrounds (Snowden *et al.* 1992; Snowden & Freyberg 1993) can be scaled from the counts in a surrounding annular region. We use a circular region of $2'$ radius for the Dumb-

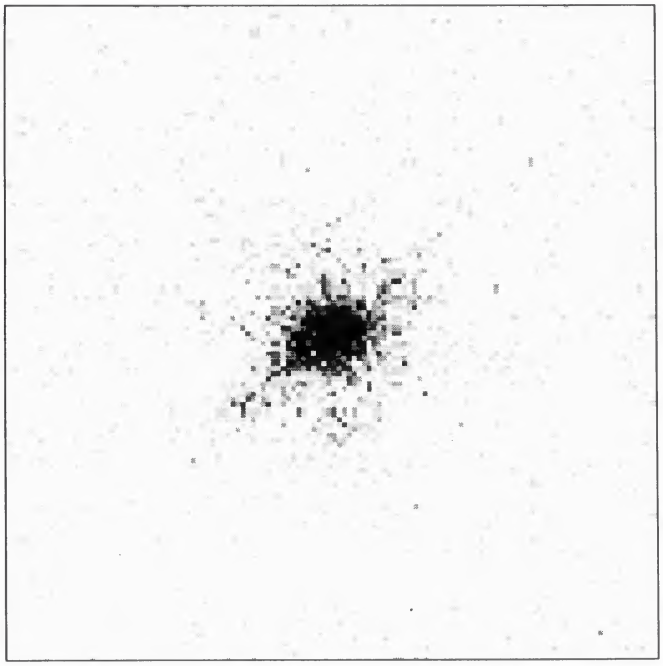

FIG. 1. *ROSAT* PSPC image of the Dumbbell Nebula, 0.1–0.41 keV. The box is 615″ on each side. North is at the top and east is to the left.

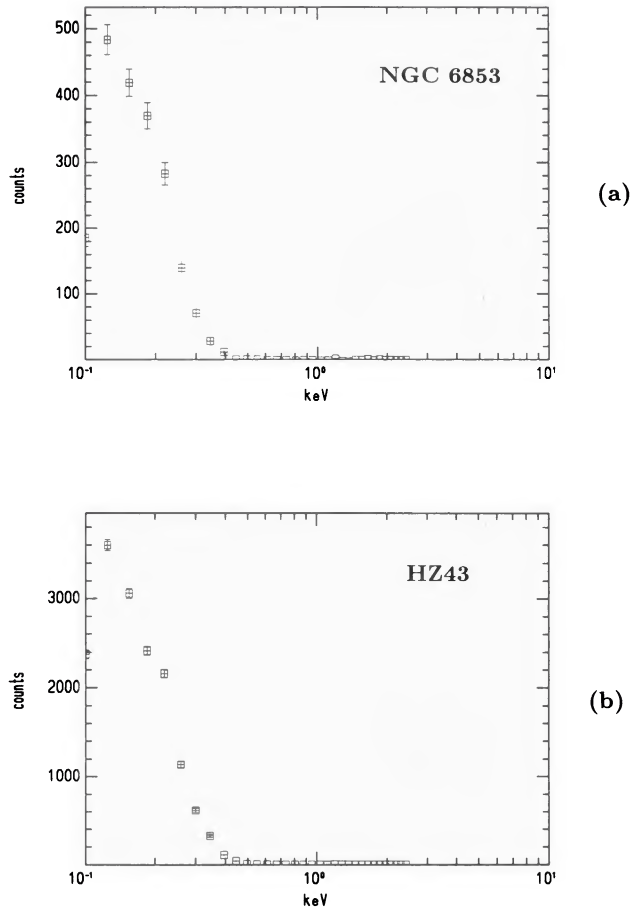

FIG. 2. *ROSAT* x-ray spectra of (a) the Dumbbell and (b) HZ43.

bell source and an annulus at radius of 190″–275″ for background. We find a total of 1852 counts within the circular region; 1804 counts are source and 48 counts are background. The background-subtracted x-ray spectrum of the Dumbbell [Fig. 2(a)] is extremely soft; hardly any counts are detected above PI channel 40 (0.4 keV).

We compared our results for the Dumbbell to those derived from the *ROSAT All Sky Survey* by Kreysing *et al.* (1992). They reported a SASS count rate of 0.5 cts s^{-1}, corresponding to a total of 190 cts, and 174 source cts. Their higher SASS count rate is probably due to their higher background rate and their inclusion of PI channels 8–10. Despite the small number of counts they detected, their spectrum is qualitatively similar to what we show in Fig. 2(a). (Note that our spectrum is plotted in observed detector counts, while their spectrum has been deconvolved with the detector response matrix.) Their spectrum shows an additional data point below 0.1 keV because the *All Sky Survey* was carried out by PSPC1 at the high gain state for which PI channels 8–10 (0.08–0.1 keV) were still good. However, their spatial distribution of x-ray emission is significantly different from ours shown in Fig. 1.

We examined our PSPC observations in four time intervals individually and found them qualitatively similar. The difference between our x-ray distribution and Kreysing *et al.*'s (1992) was puzzling at first until we were directed to the PSPC's problem of an "electronic ghost image" at the lowest energy band, PI channels 8–19 (Snowden *et al.* 1992).

3. ELECTRONIC GHOST IMAGE

The PSPC is an imaging proportional counter that uses induced charge on crossed cathode wires to obtain the position of incident photons (Briel & Pfeffermann 1986). For very low pulse-height events, it is possible that only one cathode in one or both directions has signals above the detection threshold, in which case the position determination degenerates to the position of the nearest cathode, yielding a line or a point. These falsely registered events create regularly spaced enhancements in images displayed in detector coordinates, and widen the point spread function in a complicated way. Nousek & Lesser (1992), Snowden *et al.* (1992), and Lesser & Nousek (1992) have discussed this problem extensively and called it an electronic ghost image (EGI). The EGI problem affects the R1 band (PI channel 8–19) strongly, and the R2 band (PI channels 20–41) only slightly (Snowden *et al.* 1992).

The x-ray emission detected in the Dumbbell is unfortunately strongest at the softest energy band where the EGI problem is the worst. To investigate the effects of EGI, we use the white dwarf HZ43 as a control object, since it is a point source and its x-ray spectral shape is similar to that of the Dumbbell (see Fig. 2). Observation No. 100018 of HZ43, a 194 s exposure made with PSPC1 on 1990 June 19, was kindly provided to us by the *ROSAT* staff at NASA/GSFC. We will examine the images in three energy bands: PI channels 8–10, 11–19, and 20–41. The latter two bands correspond to *ROSAT* R1L and R2 bands defined by Snowden *et al.* (1992); we will call the first

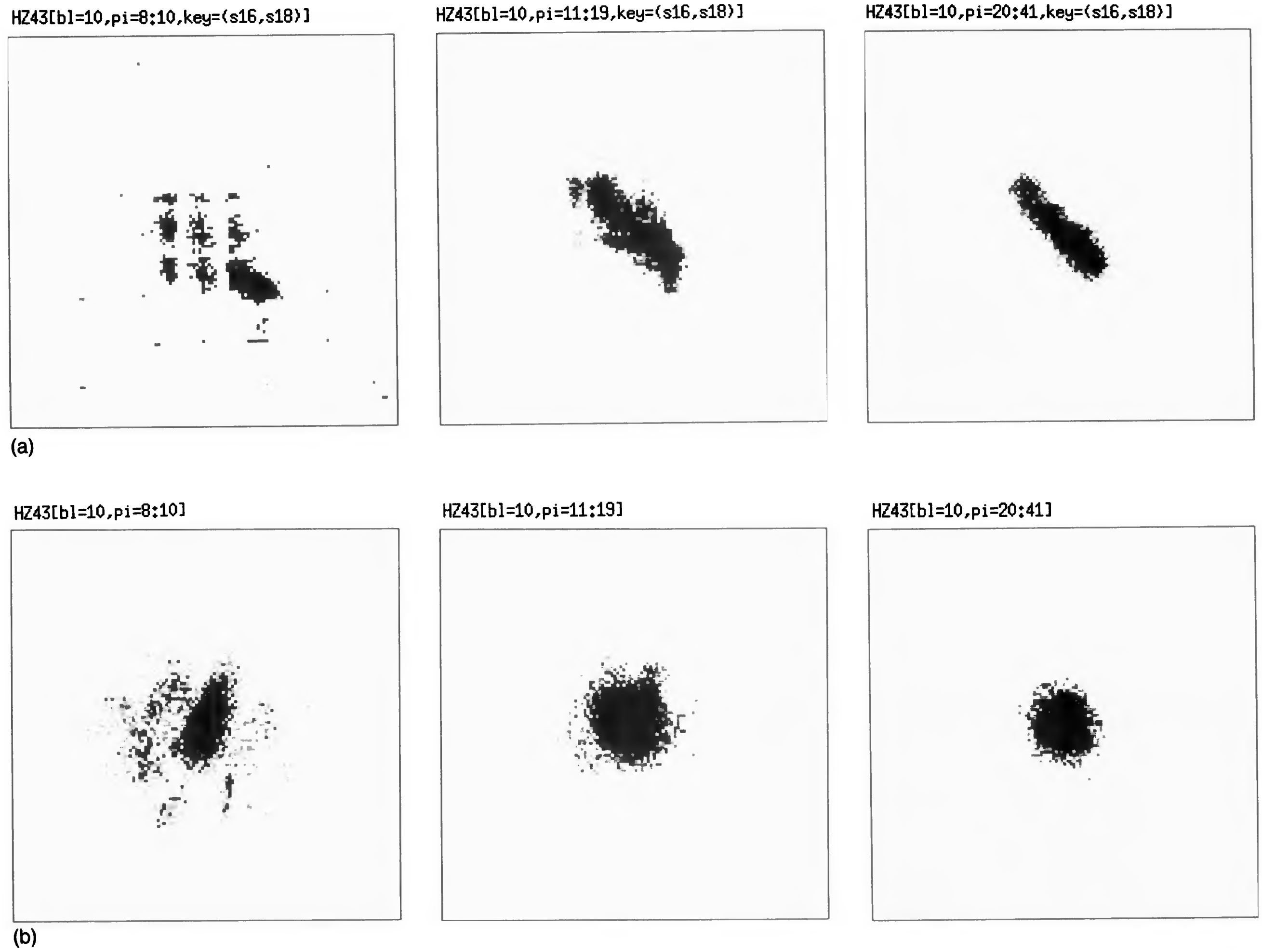

FIG. 3. *ROSAT* PSPC images of HZ43 in (a) detector coordinates and (b) sky coordinates. Each row contains three maps in R0 (PI channels 8–10), R1L (PI channels 11–19) and R2 (PI channels 20–41) bands, respectively. Each box is $615'' \times 615''$.

band R0 for convenience. The R0 band is fine for PSPC1 and PSPC2 at the high gain state, but is corrupted for PSPC2 at the low gain state.

We first use HZ43 to demonstrate the EGI effects. Figure 3(a) displays HZ43 in detector coordinates in the three energy bands described above, and Fig. 3(b) displays the corresponding images in sky coordinates. In the R0 band where the EGI effect is the most prominent, HZ43 shows an array of bright spots in the detector map, and appears to contain an elongated core and an extended halo in the sky map. The regularly spaced spots in the detector map are a typical signature of EGI. In the R2 band where the EGI effect is not so severe, HZ43 shows essentially the spacecraft wobble motion in the detector map, and appears as a point source in the sky map. The images in the R1L band show an intermediate behavior.

Figure 4(a) shows the Dumbbell in detector coordinates in R0, R1L, and R2 bands, and Fig. 4(b) shows the Dumbbell in sky coordinates. The Dumbbell was observed with PSPC2 at the low gain state, so the R0 band is corrupted; however, we still see signatures of EGI in these images. In the R1L band, regularly spaced brighter spots are visible in the detector map, and the Dumbbell appears extended in the sky map with morphology resembling that of HZ43 in the R0 band. In the R2 band, the Dumbbell shows the spacecraft wobble in the detector map, and appears as a point source in the sky map. This is similar to the situation for HZ43.

The comparison between HZ43 and the Dumbbell suggests that the extended morphology of the Dumbbell in the R1L band is most likely a result of EGI. Furthermore, the R1L and R2 bands are so close in energy that we should not see drastic changes between these two bands. Therefore, we believe that the R2 image should be used to study the distribution of x-ray emission in the Dumbbell Nebula.

4. IS THE DUMBBELL A POINT SOURCE?

We compare the spatial properties of the Dumbbell and HZ43 in the R2 band to determine whether the Dumbbell is more extended than a point source. Our observation of the Dumbbell is still quite noisy compared to HZ43, so we have experimented with various ways of blocking and smoothing the data to suppress noises while maintaining as high a spatial resolution as possible. For the image of HZ43 we can obtain a satisfactory S/N ratio without degrading the spatial resolution if we block the data by a factor of 2 then smooth it by a Gaussian with a sigma of 4

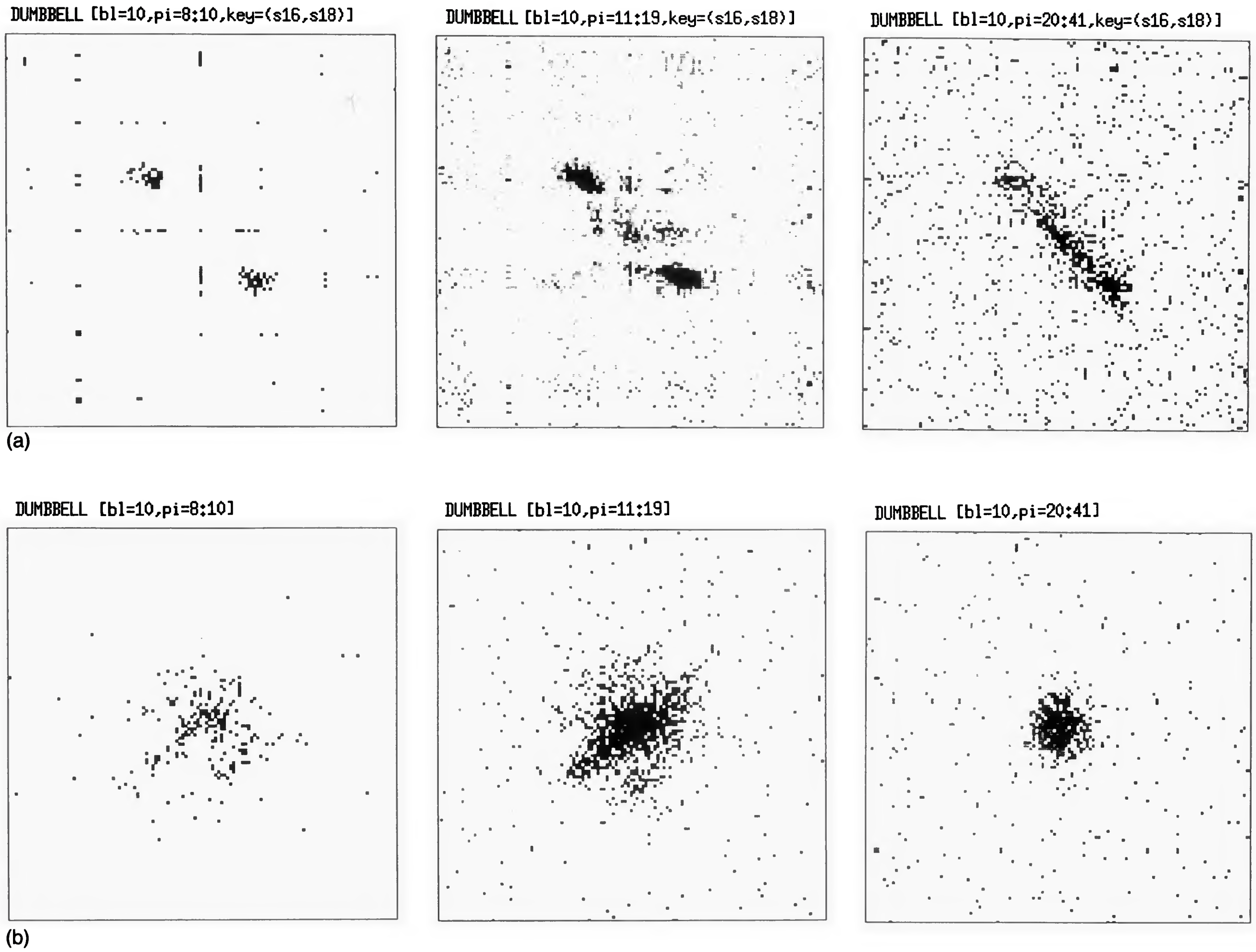

FIG. 4. *ROSAT* PSPC images of the Dumbbell in (a) detector coordinates and (b) sky coordinates. Each row contains three maps in R0 (PI channels 8–10), R1L (PI channels 11–19) and R2 (PI channels 20–41) bands, respectively. Each box is 615″×615″.

pixels. After these operations, the surface brightness contours of HZ43 become reasonably smooth and the FWHM is 46″±6″; this large error is due to an elongation in the star image. The Dumbbell, on the other hand, is still quite noisy, so we have to average over the central 30″ strip to derive the average surface brightness profile. The average surface brightness profiles of HZ43 and the Dumbbell are shown in Fig. 5. The FWHM of HZ43 is 44″±5″, and for the Dumbbell about 50″±5″ in these plots. Considering that the image of HZ43 has a roughly elliptical core, 40″×53″, this small difference in surface brightness FWHM between HZ43 and the Dumbbell is completely consistent with a point source in the Dumbbell. We conclude that there is no evidence for extended x-ray emission in the Dumbbell, and the detected x-ray emission is from the central star.

There are, in fact, other reasons not to expect diffuse x-rays from the Dumbbell. The central star of the Dumbbell is on the cooling track in the H–R diagram (Kaler 1983), and stars at this evolutionary stage have such high surface gravity that no strong stellar winds are expected. Indeed, the UV spectrum of the central star in the Dumbbell does not show any P Cygni profiles to indicate a fast stellar wind (Bohlin *et al.* 1982). Without a strong fast stellar wind, we do not expect to see diffuse x-ray emission from shocked fast wind according to the models mentioned earlier.

5. STELLAR TEMPERATURE OF THE DUMBBELL

The spatial information of the soft x-ray emission from the Dumbbell is invalid at the lowest energy channels; however, the spectral information is still valid. We can fit the x-ray spectrum with a blackbody model to determine the stellar temperature. The absorption H column density, estimated from the extinction A_V of 0.1–0.4 mag (Cahn *et al.* 1992) and a galactic gas-to-dust ratio of $N_H/A_V = 1.5\times10^{21}$ cm^{-2} mag^{-1} (Bohlin *et al.* 1978), is $\log(N_H) = 20.1$–20.8. For this range of $\log(N_H)$ any reasonable spectral fit would require a temperature below 0.012 keV; however, PROS is not able to handle such low temperature.

If $\log(N_H)$ toward the Dumbbell is 19.0 or 19.5, the best-fit temperature would be 147 000 or 136 000 K, the unabsorbed flux would be 4.0×10^{-12} or 8.2×10^{-12} erg cm^{-2} s^{-1}, and the luminosity in *ROSAT* band would be 3×10^{31} or 6×10^{31} erg s^{-1}, respectively. Figure 6 shows the x-ray spectrum and a blackbody model fit with

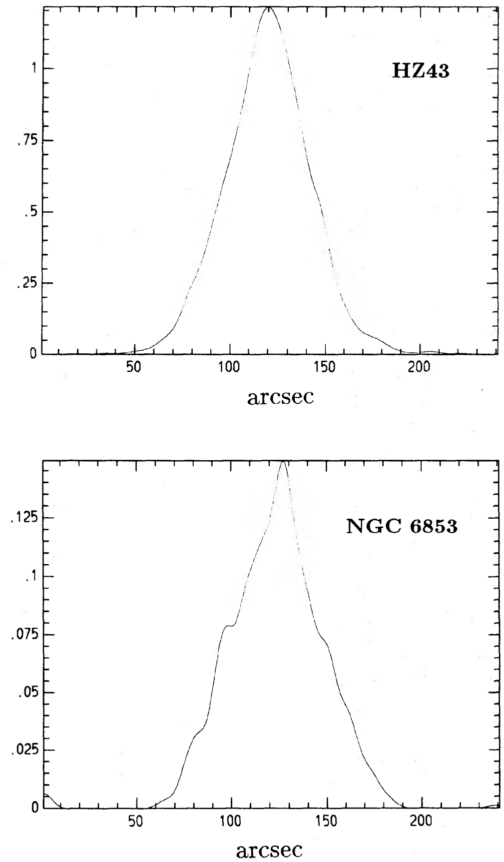

FIG. 5. Average surface brightness profiles of HZ43 and the Dumbbell.

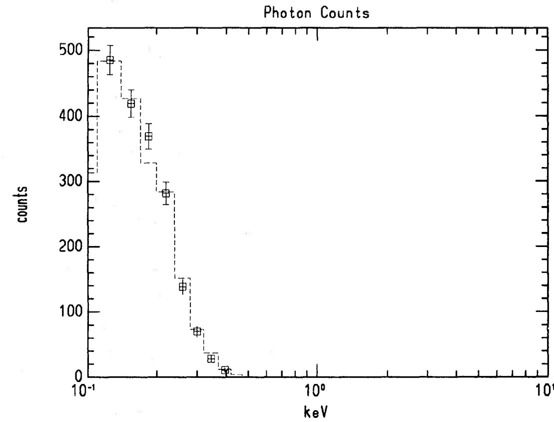

FIG. 6. X-ray spectrum of the central star of the Dumbbell and a blackbody model fit with $kT=0.0122$ keV, and $\log(N_H)=19.5$.

$\log(N_H)=19.5$ and a stellar temperature of 136 000 K. It is conceivable that for $\log(N_H)=20.2$–20.8 the blackbody temperature would be $\leqslant$136 000 K, and luminosity would be $\geqslant 6\times10^{31}$ erg s^{-1}. This temperature is very close to the best determined Zanstra temperature of 137 000 K (Kaler 1983), and suggests that the star behaves reasonably close to a blackbody with no emission edges.

6. CONCLUSION

We have analyzed the *ROSAT* PSPC observations of the Dumbbell Nebula and find that the "extended" x-ray emission reported by Kreysing *et al.* (1992) is a result of an electronic ghost image at the soft energy bands. The image of the Dumbbell in the R2 band (PI channels 20–41) is consistent with that of a point source. We conclude that the x-ray emission from the Dumbbell is stellar in origin. The best blackbody model fit of the spectrum indicates a stellar temperature of $\leqslant$136 000 in excellent agreement with the previously determined Zanstra temperatures.

Note added in proof: We received our *ROSAT* HRI data of the Dumbbell Nebula after this paper was accepted. The 3.6 ks HRI observation shows a point source at the position of the central star. The FWHM of the surface brightness profile is about 8″, slightly broader than that for HZ43 reported in *ROSAT* Mission Description. The ratio between PSPC count rate and HRI count rate is 9.8 ± 1.1, consistent with that for HZ43. We conclude that the HRI data support the stellar origin of the x-ray emission from the Dumbbell Nebula.

We thank Eric Schlegel for his patient instruction of PROS, and Robert Petre and Steve Snowden for helpful discussions. We particularly want to thank John Nousek for his suggestions on how to use PROS to examine electronic ghost images. We are also grateful to Koji Mukai for help in interpreting WFC observations, and to Richard Mushotzky for enlightening conversations. J.B.K. acknowledges support from NSF Grant No. AST91-15030, K.B.K. from NASA Grant No. NAG5-1888 and a grant from the Research Corporation, and Y.H.C. from NASA Grant Nos. NAG5-1755 and NAG5-1900.

REFERENCES

Apparao, K. M., & Tarafdar, S. P. 1989, ApJ, 344, 826
Bochkarev, N. G. 1988, Nature, 332, 518
Bohlin, R. C., Harrington, J. P., & Stecher, T. P. 1982, ApJ, 252, 635
Bohlin, R. C., Savage, B. D., & Drake, J. F. 1978, ApJ, 244, 132
Briel, U. G., & Pfeffermann, E. 1986, Nucl. Instrum. & Methods, A242, 376
Cahn, J., Kaler, J. B., & Stanghellini, L. 1992, A&AS 94, 399
Frank, A., Balick, B., & Riley, J. 1990, AJ, 100, 1903
Icke, V. 1991, A&A, 251, 369
Kahn, F. D. 1989, in Planetary Nebulae, IAU Symposium No. 131, edited by S. Torres-Peimbert (Kluwer, Dordrecht), p. 411
Kaler, J. B. 1983, ApJ, 271, 188
Knapp, G. R. 1989, in Planetary Nebulae, IAU Symposium No. 131, edited by S. Torres-Peimbert (Kluwer, Dordrecht), p. 381
Kreysing, H. C., Diesch, C., Zweigle, J., Staubert, R., Grewing, M., & Hasinger, G. 1992, A&A, 264, 623
Kwok, S. 1983, in Planetary Nebulae, IAU Symposium No. 103, edited by D. R. Flower (Reidel, Dordrecht), p. 293

Kwok, S., Purton, C. R., & FitzGerald, P. M. 1978, ApJ, 219, L125
Leahy, D. A. 1985, MNRAS, 217, 69
Lesser, A., & Nousek, J. 1992, BAAS, 24, 1196
Nousek, J., & Lesser, A. 1992, presented in ROSAT Workshop, Boston
Patriarchi, P., & Perinotto, M. 1991, A&AS, 91, 325
Snowden, S. L., Burrows, D. N., & Mendenhall, J. A. 1992, presented in ROSAT Workshop, Boston, November 5, 1992
Snowden, S. L., & Freyberg, M. J. 1993, ApJ, 404, 403
Snowden, S. L., Plucinsky, P. P., Briel, U., Hasinger, G., & Pfeffermann, E. 1992, ApJ, 393, 819
Tarafdar, S. P., & Apparao, K. M. 1988, ApJ, 327, 342
Weaver, R., McCray, R., Castor, J. I., Shapiro, P., & Moore, R. 1977, ApJ, 218, 377