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QD Wang

University of Massachusetts - Amherst

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Q. Daniel Wang

Astronomy Department, University of Massachusetts, Amherst, MA 01003, USA

Email: wqd@astro.umass.edu

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ABSTRACT

We present a *ROSAT* and *ASCA* study of the *Einstein* source X-9 and its relation to a shock-heated shell-like optical nebula in a tidal arm of the M81 group of interacting galaxies. Our *ASCA* observation of the source shows a flat and featureless X-ray spectrum well described by a multi-color disk blackbody model. The source most likely represents an optically thick accretion disk around an intermediate mass black hole ($M \sim 10^2 \mathrm{M}_\odot$) in its high/soft state, similar to other variable ultraluminous X-ray sources observed in nearby disk galaxies. Using constraints derived from both the innermost stable orbit around a black hole and the Eddington luminosity, we find that the black hole is fast-rotating and that its mass is between $\sim 20/(\cos\ i)\ \mathrm{M}_\odot - 110/(\cos\ i)^{1/2}\mathrm{M}_\odot$, where i is the inclination angle of the disk. The inferred bolometric luminosity of the accretion disk is $\sim (8 \times 10^{39}$ ergs s$^{-1})/(\cos\ i)^{1/2}$. Furthermore, we find that the optical nebula is very energetic and may contain large amounts of hot gas, accounting for a soft X-ray component as indicated by archival *ROSAT* PSPC data. The nebula is apparently associated with X-9; the latter may be powering the former and/or they could be formed in the same event (e.g., a hypernova). Such a connection, if confirmed, could have strong implications for understanding both the birth of intermediate mass black holes and the formation of energetic interstellar structures.

Subject headings: X-rays: galaxies — ISM: binaries and bubbles — galaxies: individual (M81)

1. Introduction

One of the most enigmatic X-ray-emitting objects is the source X-9 (1E 0953.8+6918), discovered with the *Einstein Observatory* in the field close to the galaxy M81 (Fig. 1; Fabbiano 1988). The source is located about $12\farcm5$ from the nucleus of the galaxy and $2'$ from the galaxy's dwarf companion Ho IX ($1'$ corresponds to a projected separation of 1 kpc at the distance $D = 3.6$ Mpc; Freedman et al. 1994). The 0.2–4 keV flux of the source is only about a factor of ~ 2 lower than the flux of the nucleus (a LINER). X-9 was also detected in subsequent *ROSAT* and *ASCA* observations at comparable flux levels. Clearly the source is not a transient. X-9 does, however, exhibit significant sporadic timing variability and therefore must primarily be a compact source (Immler & Wang 2001; Ezoe et al. 2001). Interestingly, Miller (1995) discovered that the source was projected inside a very unusual Hα-emitting nebula (Fig. 1), which also emits strong [SII] and [OI] lines. He concluded that this nebula was shock-heated and might be a very energetic supernova remnant (SNR) or a superbubble. Furthermore, the nebula is apparently located within a nearly "quiescent" massive atomic and molecular gas concentration in a tidal arm (Concentration I, Yun et al. 1994; Fig. 1a). The lack of a significant stellar population in this region has further led to the suggestion of the concentration being a protogalaxy (Henkel et al. 1993). The nature of this combination of stellar and interstellar features remains unknown.

In this paper we present results from the analysis of a dedicated *ASCA* and archival *ROSAT* observations of the intriguing X-ray source X-9. We concentrate on the nature of the source and its relation to the environs, not on the detailed processes involved in the emission and evolution of the source.

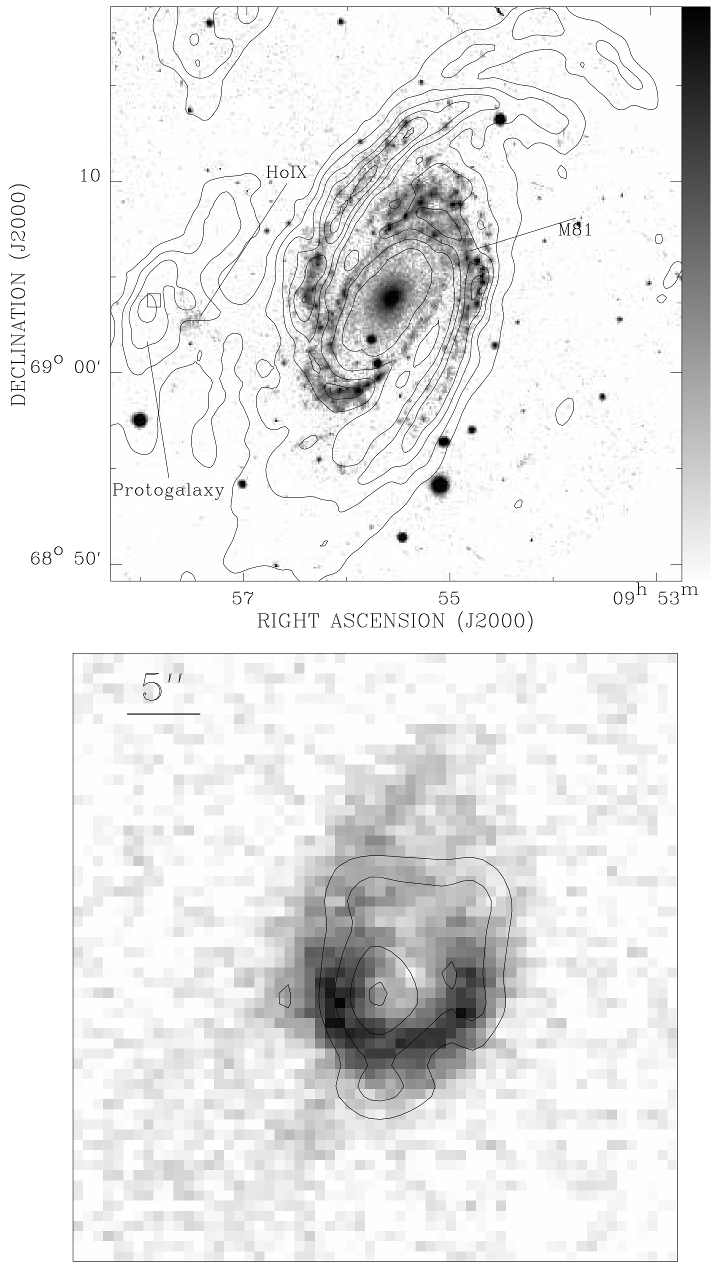

Fig. 1.— The field including M81 in near-UV (∼ 2490Å; Hill et al. 1992), with overlaid HI contours at 5, 10, 15, 20, and 25 $\times 10^{20}$ cm^{-2} (upper panel). A close-up of the region outlined by a box in the field of the protogalaxy is shown in the lower panel. The Hα image is provided by Miller (1995) and the *ROSAT* HRI intensity contours are plotted at 0.24, 0.34, 0.44, and 0.54 × counts s^{-1} arcmin^{-2}. The structure of the X-ray emission is uncertain because of the complicated PSF of the observations at the large off-axis angle (Immler & Wang 2001).

2. X-ray Observations

Our study is based primarily on our *ASCA* observation of X-9, taken in April of 1999. Located at R.A., Dec. (J2000) = $9^{\rm h}57^{\rm m}54^{\rm s}$, $69^\circ03'50''$ (Source # H44/P66; Immler & Wang 2001), the source was observed with the two pairs of the SIS (exposure 41 ks) and GIS detectors (35 ks). The SIS, however, experienced a loss of sensitivity to low-energy ($\lesssim$ 2 keV) photons since approximately late 1994. This loss increased with time and reached as much as 40% at the time of our observation. No method has been proposed to quantify this loss. Nevertheless, the data from the SIS, with a better spectral resolution than the GIS, show no sign of any emission line in the spectrum of X-9. The present study therefore includes only the data from the GIS, which had a spectral resolution of $\delta E/E \approx 0.08(6\ {\rm keV}/E)^{0.5}$ over the 0.5–10 keV band and a 50% half power diameter of $\sim 3'$ on axis.

We followed the standard data processing procedure as detailed by Day et al. (1995), using the HEAsoft software package. We extracted on-source counts from an aperture of $4\overset{'}{.}5$ radius and estimated the background contribution in a circle of $15'$ radius around the GIS image center, excluding regions of $6'$ radii around the M81 nucleus and X-9. The data from the two GIS detectors were first combined and then loaded into the software XSPEC for spectral analysis.

We also incorporated archival data from *ROSAT* PSPC and *ASCA* GIS observations in our analysis. All these observations were pointed at either SN1993J or M81 and covered a period of about 9 years; X-9 was included in the field of view at large off-axis angles ($\gtrsim 10'$) in each of the observations. The archival data were partly analyzed by Ezoe et al. (2001) and by Immler & Wang (2001), concentrating on timing variability. We extracted the archival GIS data in a similar fashion as described above for our observation. We combined PSPC spectra extracted from an on-source aperture of $1\overset{'}{.}3$ radius and a background annulus

of inner and outer radii, $1'\!.8$ and $5'$, respectively. All the spectra are corrected for off-axis PSF and effective area effects.

3. X-ray Data Analysis and Results

Because X-9 is variable and lacks an apparent point-like optical counterpart, we concentrate on spectral models that are appropriate for a compact X-ray source. We first fit the spectrum from our own *ASCA* observation alone. Table 1 summarizes results from the fits of several commonly used models. The power law is characteristic of AGN spectra in the *ASCA* band, although they sometimes exhibit soft *excesses* at energies $\lesssim 1$ keV and/or hard X-ray bumps at $\gtrsim 10$ keV. Previous analysis by Ezoe et al. (2001) showed that a power law gave an acceptable fit to an average X-ray spectrum of X-9, extracted from archival GIS observations. The quality of this spectrum is problematic, however, chiefly because of the poor PSF at off-axis angles greater than $10'$. There might also be substantial uncertainties in background subtraction and energy-dependent PSF-related correction as well as in the calibration of the instrument energy response. Indeed, the power law model fits our high quality GIS spectrum of X-9 poorly. The spectrum is convex-shaped with flux *deficits* at both low and high energy ends and shows no sign of an Fe K line at $\sim 6.4 - 6.7$ keV, which often appears in the spectra of bright AGNs. Therefore, X-9 is unlikely to be an AGN.

Could X-9 be Galactic in origin? We considered the black body, which is a reasonably good description of X-ray emission from the surface of an isolated neutron star. The model, however, is much too sharply peaked to satisfactorily represent the spectrum of X-9. Raymond & Smith optically thin thermal plasma also gives an unacceptable fit to the spectrum. Our *ASCA* observation with a timing resolution up to ~ 0.1 ms was designed partly to test the hypothesis that the source might be a moving X-ray pulsar, which could

also power the optical nebula. Our FFT and period folding timing analyses of X-9, however, show no significant periodic signal in the period range from 1 ms to several hours.

We find that an accreting black hole model is an attractive option for the X-9 spectrum (Fig. 2). The source, if at the distance of M81 and radiating isotropically, has an X-ray luminosity of $\sim 1 \times 10^{40}$ ergs s^{-1}. This luminosity is a factor of $\sim 10^2$ greater than the Eddington luminosity for a 1.4 $M_\odot$ accreting neutron star, but is within the range of the so-called ultra-luminous X-ray sources (ULXSs), which are detected typically in disk galaxies and considered as accreting BHs in the high/soft state (Colbert, & Mushotzky 1999; Makishima et al. 2000). The X-ray spectra of these sources are well described by the multi-color disk blackbody (MCD) model (XSPEC model *diskbb*). Indeed, the model fits the spectrum of X-9 well (Table 1).

Next, we jointly fit the GIS and PSPC spectra with the MCD model (Fig. 2). The PSPC data are particularly sensitive to soft X-ray emission and absorption. Because the flux of X-9 varies with time (amplitude of variability exceeding a factor of ~ 2.5; cf. Fig. 3 in Immler & Wang 2001) and because the spectrum could also change accordingly, we allow both $T_{\rm in}$ and $K_{\rm MCD}$ to be different for the GIS and PSPC spectra and joint-fit the X-ray absorbing gas column density. The MCD model gives a good fit to the spectra ($\chi^2/n.d.f. = 143/166$). The fitted column density is $1.0(0.9 - 1.1) \times 10^{21}$ $\rm cm^{-2}$ (90% confidence limits), compared to the expected Galactic contribution of $\sim 5 \times 10^{20}$ $\rm cm^{-2}$ in the direction. This extra absorption is consistent with the hypothesis that X-9 is located inside Concentration I. The MCD spectral parameters for the GIS data are nearly identical to those from the above single spectrum fit. But the spectral parameters for the PSPC data are rather different: $T_{\rm in} = 0.59(0.55 - 0.63)$ and $K_{\rm MCD} = 1.7(1.3 - 2.2)$.

Table 1. Model fits to the *ASCA* GIS spectrum

Model	Parameter[a]	$\chi^2/n.d.f.$
Power-law	energy slope $= 1.3(1.2-1.4)$	240/140
	$N_{\rm H} = 5.0(4.5-5.6)\times 10^{21}$ cm^{-2}	
Blackbody	Temperature $= 0.74$ keV	511/140
	$N_{\rm H} = 2.3(0.9-3.2)\times 10^{21}$ cm^{-2}	
MCD	$T_{\rm in} = 1.34(1.31-1.37)$ keV	93/130
	$K_{\rm MCD} = 0.20(0.18-0.22)$	
	$L_{\rm x} = (1\times 10^{40}/\cos\, i)$ ergs s^{-1}	
	$N_{\rm H} = 3.0(0.0-6.1)\times 10^{20}$ cm^{-2}	

[a]$T_{\rm in}$ is the characteristic temperature of the disk at its inner radius. The normalization of the MCD model is defined as $K_{\rm MCD} = (R_{\rm in}/D)^2 \cos\, i$, where $R_{\rm in}$ is the inner disk radius in units of km, the distance to the source D is in units of 10 kpc, and i is the disk inclination angle. The disk luminosity $L_{\rm x}$ is calculated in the 0.5–10 keV band. Uncertainties in the parameter estimates (enclosed in parentheses) are at the 90% confidence limits.

4. Discussion

The above spectral characteristics of X-9, together with its strong aperiodic variation (Immler & Wang 2001) and its lack of periodicity, argues against a scenario of the source as a Galactic compact object. Indeed, at the source's Galactic position of $l, b = 143^\circ, 18^\circ$, there is little room for such a scenario. Ezoe et al. (2001) have made additional arguments against the Galactic origin of X-9, based primarily on its high X-ray to optical emission ratio. In contrast, the model of X-9 as an accreting BH inside Concentration I at the M81 distance naturally accounts for the sporadic timing behavior, the convex-shaped spectrum, the excess absorption, and the large X-ray flux of the source.

But the apparent discrepancy between the GIS and PSPC spectral characteristics demands an explanation. The low $T_{\rm in}$ as inferred from the PSPC spectrum is very abnormal, compared with similar ULXSs observed with *ASCA*. X-9 also shows strong flux variation: e.g., 2.5×10^{-12} ergs s^{-1} cm^{-2} for the PSPC spectrum vs. 5.1×10^{-12} ergs s^{-1} cm^{-2} for the GIS spectrum over the overlapping 0.5–2 keV band. But this variation is typical for ULXSs and is well within the range inferred from the archival GIS spectra of X-9. Indeed, the MCD model provides satisfactory fits to all individual GIS spectra, and $T_{\rm in}$ is always greater than 1.2 keV. Clearly, the MCD model with the abnormal low $T_{\rm in}$ cannot be a fair characterization of the GIS spectra. It is important to note that the MCD model has been tested primarily on X-ray spectra of heavily absorbed Galactic black hole candidates. It is possible that the model does not adequately describe the soft X-ray emission from the accretion disk of X-9.

Alternatively, the PSPC spectrum of X-9 may contain a significant soft X-ray contribution from diffuse hot gas. This may be expected in the region enclosed by the shock-heated optical nebula, or from relativistic particles accelerated in an expanding shock related to the nebula. The narrow bandwidth and very limited spectral resolution of

the PSPC data, however, do not allow for a useful spectral decomposition of such a soft component from the uncertain disk emission of the source at the time of the observations. A spatial analysis of the archival *ROSAT* PSPC and HRI data also shows evidence for the extended X-ray emission around the centroid of X-9 on scales comparable to the size of the nebula. But various systematic uncertainties (e.g., the source centroid shift caused by the off-axis instrumental point spread function) prevent us from a definitive measurement of the extended emission.

4.1. X-9 as an Accretting IMBH

Assuming that the MCD model is correct, we can estimate the mass of the BH: $M_{\rm BH} = (41{\rm M}_\odot)\alpha^{-1}(K_{\rm MCD}/\cos\, i)^{1/2}$, where α is the ratio of the inner disk radius to the last stable orbit radius of a non-rotating (Schwarzschild) BH, and both $K_{\rm MCD}$ and i are defined in the note to Table 1. Adopting $K_{\rm MCD}$ in Table 1 gives $M_{\rm BH} = 18/(\alpha^2 \cos\, i)^{1/2}{\rm M}_\odot$. For a general rotating Kerr BH, $\alpha \gtrsim 1/6$ (e.g., Zhang et al. 1997) and thus $M_{\rm BH} \lesssim 108{\rm M}_\odot/(\cos\, i)^{1/2}$. The model, however, does not include various general relativistic effects (e.g., light bending). Ongoing modeling of such effects shows that the cosine law is approximately preserved for Schwarzschil BHs and that for extreme Kerr BHs the effective $\cos\, i = 0.17 - 0.4$ for $i = 5^\circ - 85^\circ$ (Zhang et al. 2001). So the range of variation can be considerably smaller than the cosine law. Following Makishima et al. (2000), we can also estimate the bolometric luminosity of the disk as $L_{bol} = (8 \times 10^{39}\ {\rm ergs\ s^{-1}})/(\cos\, i)^{1/2}$. Because L_{bol} should typically be smaller than, or at most comparable to, the Eddington luminosity $1.3 \times 10^{38}(M_{\rm BH}/{\rm M}_\odot)$, we obtain $\alpha \lesssim 0.76(\cos\, i)^{1/2}$, indicating that the BH is fast-rotating ($\alpha < 1$) and that $M_{\rm BH} \gtrsim 24{\rm M}_\odot/\cos\, i$. The 90% statistical uncertainties in these mass limits are about 10%.

4.2. Optical Nebula

The presence of the unusual shell-like optical nebula is an important part of the mystery about X-9 (Fig. 1b). Optical spectroscopy of the nebula shows that its mean heliocentric velocity ($\sim 47-52$ km s^{-1}) agrees with the velocity ($\sim 45-65$ km s^{-1}) of the HI concentration (Adler & Westpfahl 1996; Miller 1995). The HI velocity field further shows that the concentration is part of the M81 group (Miller 1995). In contrast, the dwarf galaxy Ho IX has an optical heliocentric velocity of 119 ± 60 (de Vaucouleurs et al. 1991) and is offset spatially from the centroid of the HI concentration. Therefore, Ho IX may not be related to either the HI concentration or the nebula (Fig. 1a).

What might be the origin of the nebula around X-9? At the distance to M81, the nebula has an Hα luminosity $L_{\rm H\alpha} \sim 1 \times 10^{38}$ ergs s^{-1} (Miller & Hodge 1994), which is about three times more luminous than the bright SNR N49 in the LMC (Vancura et al. 1992). But the most distinct difference between the two is their sizes: ~ 250 pc $\times$ 475 pc for the X-9 nebula (Miller 1995) vs. 8 pc radius for N49. If the nebula is heated primarily by a shock (Miller 1995), a significant fraction (parameterized here as ξ) of $L_{\rm H\alpha}$ may then be produced by the excitation as pre-shock hydrogen atoms drift into the post-shock region (e.g., Cox & Raymond 1985). Optical spectroscopy so far, however, places only an upper limit of 300 km s^{-1} on the shock velocity of the X-9 nebula (Miller 1995). Assuming a shock velocity $v_2 \gtrsim 2$ (in units of 10^2 km s^{-1} and the standard case B (that is, optically thick for all Lyman recombination lines), we can estimate from $L_{\rm H\alpha}$ the pre-shock neutral gas density as $n_o \sim (10 \text{ cm}^{-3}) v_2^{-1} R_2^{-2} \xi$, where R_2 (in units of 10^2 pc) is the characteristic radius of the nebula. The kinetic energy is then $E_k \sim (1 \times 10^{53} \text{ ergs}) v_2 R_2 \xi$ if n_o is spatially uniform. This is likely to be an overestimate because the bulk of the Hα-emitting gas is expected to arise in dense filaments and clouds in which shock velocity tends to be low. Furthermore, a substantial fraction of the Hα emission may also be due to the ionization

by the X-ray source (§4.3). Nevertheless, comparisons with known SNRs suggest that the X-9 nebula appears to energetic to be due to a single normal supernova (SN).

Could the optical nebula then be a superbubble produced by multiple SNe and fast stellar winds of massive stars (e.g., Mac Low & McCray 1988)? At the position of X-9, there is indeed a fuzzy blue object which may represent a stellar cluster ($m_{\rm B} = 20$; Henkel et al. 1996; Miller 1995). If this is the case, the stellar cluster should then have an age $t_s \gtrsim 10^7$ yr, as young stars do not appear to contribute much to the ionization of the optical nebula and no far-UV emission peak appears at the position of X-9 (e.g., Fig. 1). Comparing t_s with the expansion age of the nebula $t_e \sim 3R/5v = (1 \times 10^6 \text{ yr}) R_2 v_2^{-1}$, we find $v \lesssim (5 \text{ km s}^{-1}) R_2$. This is less than the turbulence velocity of the ISM and too small for shock-heating to effectively produce significant Hα emission. Therefore, unless being accelerated recently by an SN (or a hypernova; see later discussion) the optical nebula is probably not a superbubble created by a massive stellar cluster.

4.3. Association of the Optical Nebula and X-9

Using the log(N)-log(S) function from the *ROSAT* All Sky Survey (Hasinger et al. 1998), we estimate that the probability for a chance projection of an X-ray source comparable to, or brighter than, X-9 within a circle of $\sim 10''$ radius is only about $\sim 5 \times 10^{-7}$. Therefore, X-9 is most likely associated with the nebula.

We speculate that the optical nebula may be directly related to the presence of X-9. One possibility is that they were born together. The nebula may be an interstellar remnant of a hypernova explosion that is substantially more energetic than a normal SN. Hypernovae have been postulated as the sources of some γ-ray bursts observed at cosmological distances (Paczyński 1998; Fryer & Woosley 1998). The proposed mechanism

for hypernova explosions is the collapse of certain massive stars and/or their mergers with compact companions. Such an event leads to the formation of a BH and provides an extractable energy of $\sim 10^{54}$ ergs (Mészáros, Rees, & Wijers 1999). Hypernovae may also be responsible for some HI supershells or holes observed in the interstellar medium (ISM) of nearby galaxies (Efremov, Elmegreen, & Hodge 1998; Loeb & Perna 1998), as well as relatively young energetic shell-like nebulae (Wang 1999). The optical nebula around X-9 could well be such a hypernova remnant. The X-ray source may represent the resultant BH accreting from the materials falling back from the explosion. Although a binary may survive the explosion, the turning-on of a persistent accretion phase is expected to be long after the explosion remnant has disappeared. The soft X-ray contribution from the hypernova remnant may be significant in the PSPC spectrum, whereas the GIS spectrum is dominated by the bright accretion disk in a higher state, which makes the detection of the soft component difficult.

Another plausible scenario is that the nebula is currently powered by an intense outflow or a wind from X-9 as an accreting X-ray binary. If the nebula is purely caused by this outflow, the required mean energy output over the nebula's expansion age t_e is then a few times 10^{39} ergs s^{-1}, which is comparable to the X-ray luminosity of the source. In principle, the power of such an outflow could even be greater than the radiation luminosity of X-9, if it is similar to other types of accreting BH systems (i.e., Galactic micro-quasars or AGNs). In this case, the IMBH may be a Population III remnant (e.g., Madau & Rees 2001) and its companion may be formed from the collapse of surrounding molecular gas inside Concentration I (Henkel et al. 1993; Yun et al. 1994; Brouillet et al. 1992; Fig. 1).

X-9 may also contribute to the ionization of the nebula. The MCD model of X-9 predicts an integrated ionizing photon rate of $\sim 4 \times 10^{40}$ s^{-1} over the 0.016–0.2 keV range; photons at higher energies should mostly escape from the nebula. This rate is about a

factor of 10 greater than that estimated for LMC X-1 (a stellar mass BH candidate), which is surrounded by an X-ray-ionizing nebula (Pakull & Angebault 1986). The nebula around X-9 shows indications of X-ray ionization. First, the Hβ to Hα flux ratio (~ 0.6) of the nebula is high, indicating a high electron temperature of $\sim 10^5$ K (Miller 1995). Second, the shell-like morphology of the nebula appears to be rather diffuse, as is expected from the relative long absorption path-length of soft X-rays and its strong energy dependence (e.g., Rappaport et al. 1994).

Further scrutiny of the above scenarios and their relative importance is both desirable and possible. The nature of the blue object is yet to be determined: is it the optical counterpart of the accreting system or the outflow? The outflow may also be probed by observing its nonthermal radio emission, which should show a persistent flat or inverted radio spectrum (e.g., Fender 2001). The 20 cm radio continuum map of Bash & Kaufman (1986), which is centered on M81, does show a 3σ contour at the position of X-9. The total flux of ~ 1 mJy, if indeed associated with the outflow, is substantially greater than that observed from Galactic micro-quasar-like objects. Detailed optical spectroscopy of the nebula will be especially important for determining the expanding velocity of the nebula and will provide important constraints on the extreme UV to soft X-ray radiation properties of X-9. Such radio/optical observations, combined with future high resolution X-ray imaging and spectroscopy, should allow for a firm determination of the relation between the nebula and X-9.

In summary, the association of X-9 with both the blue object and the shell-like $H\alpha$ nebula as well as Concentration I provides an excellent opportunity for studying the nature of ultraluminous X-ray sources and for characterizing their radiation and outflow as well as their effects on the interstellar medium.

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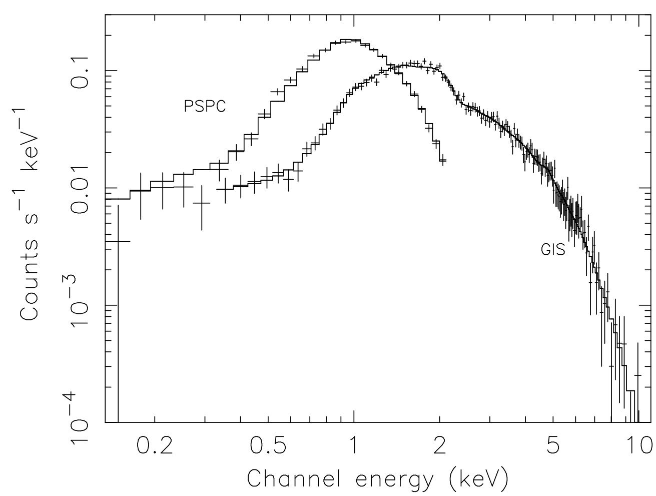

Fig. 2.— Joint fit to the combined *ASCA* GIS and *ROSAT* PSPC spectra of X-9. The histograms represent the best fit of the MCD model.

REFERENCES

Adler, D. S., & Westpfahl, D. J. 1996, AJ, 111, 735

Bash, F. N., & Kaufman, M. 1986, ApJ, 310, 621

Brouillet, N., et al. 1992, A&A, 262, L5

Colbert, E. J. M., & Mushotzky, R. F. 1999, ApJ, 519, 89

Cox, D. P., & Raymond, J. C. 1985, ApJ, 298, 651

Day, C. S. R., et al. 1995, The ABC Guide to *ASCA*Data Reduction, *ASCA* Guest Observer Facility, NASA/GSFC

de Vaucouleurs, G., et al. 1991, Third reference catalogue of bright galaxies, New York: Springer-Verlag

Efremov, Y. N., Elmegreen, B. G., & Hodge, P. W. 1998, ApJL, 501, 163

Ezoe, Y., Iyomoto, N., & Makishima, K. 2001, PASJ, 53, 69

Fabbiano, G., 1988, ApJ, 325, 544

Fender, R. P. 2001, MNRAS, 322, 31

Freedman, W. L., et al. 1994, ApJ, 427, 628

Fryer, C. L., & Woosley, S. E. 1998, ApJL, 502, 9

Hasinger, G., et al. 1998, A&A, 329, 482

Henkel, C., et al. 1993, A&A, 273, L15

Hill, J. K., et al. 1992, ApJL, 395, 37

Immler, S., & Wang, Q. D. 2001, ApJ, 554, 202

Loeb, A., & Perna, R. 1998, ApJL, 503, 35

Mac Low, M.-M., & McCray, R. 1988, ApJ, 324, 776

Madau, P., & Rees, M. J. 2001, ApJL, 551, 27

Makishima, K., et al. 2000, ApJ, 535, 632

Mészáros, P., Rees, M. J., & Wijers, R. A. M. J. 1999, New Astronomy, 4, 303

Miller, B. W. 1995, ApJL, 446, 75

Miller, B. W., & Hodge, P. 1994, ApJ, 427, 656

Paczyński, B. 1998, ApJL, 494, 45

Pakull, M. W., & Angebault, L. P. 1986, Nature, 322, 511

Rappaport, S., Chiang, E., Kallman, T., & Malina, R. 1994, ApJ, 431, 237

Wang, Q. D. 1999, ApJL, 510, 139

Yun, M. S., Ho, P. T. P., & Lo, K. Y. 1994, Nature, 372, 530

Zhang, S. N., Cui, W., & Chen, W. 1997, ApJL, 482, 155

Zhang, X., Zhang, S.N., & Yao, Y. 2001, Gamma-ray conference, Baltimore, Maryland

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