THE ASTROPHYSICAL JOURNAL, 403:L71–L74, 1993 February 1

AN INTERPRETATION OF THE NARROW POSITRON ANNIHILATION FEATURE FROM X-RAY NOVA MUSCAE 1991

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Received 1992 August 20; accepted 1992 November 5

ABSTRACT

We study the physical mechanisms responsible for producing the narrow, redshifted positron annihilation γ-ray line from X-ray Nova Muscae 1991 observed by *GRANAT*/SIGMA. We argue that the line centroid redshift is most probably of gravitational origin, and that the annihilation very likely takes place in the inner region of an accretion disk in the system. The narrow line width can then be naturally explained by a small inclination angle of the accretion disk to our line of sight. The recently measured photometric binary mass function of Remillard, McClintock, & Bailyn (1992) gives the black hole mass for this system as a function of orbital inclination angle which we find it to be $26° \pm 25°$. Assuming the accretion disk lies in the orbital plane of the system, the black hole mass is found to have a lower limit of 8 $M_\odot$, although statistics are poor. This is supported by spectral modeling of combined optical/UV/X-ray data and by a new Nova Muscae distance limit we derive of >3 kpc. The large mass for this black hole and the high binary mass ratio it implies (>15) raise a serious challenge to theoretical models of the formation and evolution of massive binaries. The γ-ray line technique introduced here can give tight constraints on orbital parameters when high-sensitivity line measurements are made by such missions as *GRO*.

Subject headings: accretion, accretion disks — binaries: close — black hole physics — line: formation — gamma-rays: theory

1. INTRODUCTION

The X-ray Nova Muscae 1991 (GRS 1121−68 = GS 1124−683, hereafter XN Mus) was discovered on 1991 January 9 by the all-sky monitors on board both the *GRANAT* and *Ginga* satellites (Lund & Brandt 1991; Makino et al. 1991) and was subsequently observed by all the X-ray and γ-ray instruments in orbit: by ART-P and SIGMA on *GRANAT* in 3-1300 keV (Grebenev, Sunyaev, & Pavlinsky 1991; Gilfanov et al. 1991), by *Ginga* in 1–37 keV (Tanaka, Makino, & Dotani 1991), and by *ROSAT* in 0.4–2.3 keV (Greiner et al. 1991). The early optical and X-ray light curve and spectral behavior of XN Mus are remarkably similar to that of the black hole system A0620−00 (=V616 Mon; Tanaka, Makino, & Dotani 1991), which suggests that XN Mus also contains a black hole. Observations at ESO (Della Valle, Jarvis, & West 1991a, b) have identified the optical counterpart of XN Mus both before and after the outburst as a K–M dwarf orbiting a compact object, probably a black hole (Della Valle et al. 1991b), located at an estimated distance of 1.4 kpc. The binary period of the system was later found to be 10.5 hr (Bailyn 1992). By modeling the *HST*/FOS observation of XN Mus together with the spectra from ART-P, NTT (Della Valle et al. 1991a) and *IUE* (Shrader & Gonzales-Riestra 1991), Cheng et al. (1992) found that the broad-band spectrum and its evolution can be well fitted by a standard blackbody thin accretion disk model (Czerny, Czerny, & Grindlay 1986). In this analysis they derived a *minimum* compact object mass of 12.5 $M_\odot$ and a distance of ~5 kpc, using the observed orbital period.

Yet the ultimate proof of the presence of a black hole in XN Mus relies on the dynamic evidence of the mass of the compact object. Optical photometry and spectroscopy of XN Mus in quiescence obtained recently at CTIO (Remillard, McClintock, & Bailyn 1992) give a mass function,

$$f \equiv \frac{(M \sin i)^3}{(M + M_c)^2} = 3.07 \pm 0.40\ M_\odot\ , \tag{1}$$

where M and M_c are the masses of the primary and companion, and i is the orbital inclination angle of the system ($i = 0$ is face-on). For reasonable values of the mass range for the K0 V–K4 V dwarf companion (0.3–0.7 $M_\odot$) and the orbital inclination angle ($i < 80°$ for lack of optical and X-ray eclipses), the compact primary has a mass $M > 3.75\ M_\odot$ and is therefore very likely a black hole (Remillard et al. 1992). To further pin down the primary mass, one needs to know more about the orbital inclination angle of the system. In principle one could deduce the inclination from optical data by modeling the ellipsoidal variations in the orbital light curve which are caused by the changing cross section of the Roche lobe–filling secondary. In practice this is difficult because it is hard to determine how much of the light one observes comes from the mass donor secondary and how much of it comes from elsewhere in the system. In A0620−00, a partial eclipse provides an additional constraint, allowing i to be determined from the orbital light curve (Haswell 1992). If the system happens to have a small inclination angle, the ellipsoidal variation may be hardly observable. In this *Letter* we show that, in a completely new approach, such geometric information can be inferred from the central energy and width of a γ-ray emission line from XN Mus.

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2. MODEL

Twelve days after the hard X-ray outburst, a most remarkable transient emission feature was observed in the high-energy spectrum of XN Mus by SIGMA (Sunyaev et al. 1992; Goldwurm et al. 1992). The line radiation was seen only for a few hours, with central energy ~480 keV and a FWHM ~60 keV. The most natural interpretation is that it is a positron annihilation line (rest-frame energy $E_0 = 511$ keV) radiated from the vicinity of a compact object and so is gravitationally redshifted by about 6%. An emission line of energy E_0 radiated at a distance r from the compact object is observed to be redshifted to $E = E_0 - \Delta E$, where $\Delta E/E_0 = 1 - (1 - r_S/r)^{1/2}$ and $r_S = 2GM/c^2$ is the Schwarzschild radius. For XN Mus, the reported annihilation radiation is centered at $E = 481 \pm 22$ keV from Goldwurm et al. (1992) and at 476 ± 15 keV from Sunyaev et al. (1992). If we adopt the mean value, 479 ± 18 keV, the redshift is then $z = \Delta E/E = 0.068 \pm 0.042$ and the annihilation radius $r = 8.2 \pm 4.6 r_S$.

There is other observational evidence that the annihilation photons are produced near the black hole. First, there is an emission feature at ~200 keV that appeared in the high-energy spectrum of XN Mus at the same time as the annihilation feature (Sunyaev et al. 1992; Goldwurm et al. 1992). This can be attributed to annihilation photons escaping from the inner region of the accretion disk and then being Compton-reflected by the outer part of the disk (Lingenfelter & Hua 1991). Second, no three-photon positronium continuum is found in the annihilation spectrum of XN Mus (Grebenev et al. 1991), suggesting that the annihilation site is hotter than 10^5 K (Bussard, Ramaty, & Drachman 1979) or much denser than 10^{14} cm^{-3} (Crannell et al. 1976) and is therefore near the black hole.

One may argue that the line redshift is due to the Doppler effect of a jet of annihilating e^+-e^- pairs emanating from the system, but we believe this is unlikely. Accretion systems usually have, if any, *two* jets in opposite directions, so we should see both blueshifted and redshifted lines. However, in XN Mus, only a redshifted component was seen. All the physical mechanisms for hiding one jet (e.g., Lorentz boosting or disk shadowing) would allow the observer preferentially to see the one which is *blueshifted* rather than the redshifted one. So the line redshift is not due to the Doppler effect unless the system produces only a single jet which happens to be moving away from us and is not obscured by the accretion disk in the system. We also draw the reader's attention to similar *transient* and *redshifted* annihilation radiation observed from the Galactic center γ-ray source 1E 1740.7−2942 by SIGMA (Bouchet et al. 1991; Sunyaev et al. 1991) and from a hard X-ray source observed by *HEAO* A-4 instrument (Briggs 1991). For comparison, we plot the original spectra of the three sources together in Figure 1. The redshifts in all three detected annihilation features are quite similar which favors their gravitational origin.

As the annihilation region is so close ($\leq 10 r_S$) to the black hole, the narrowness (~60 keV) of the annihilation feature becomes most puzzling since many physical processes may contribute to the line width including thermal, turbulent and Doppler broadening. Near the black hole, high-energy e^+-e^- pairs are thought to be created via γ-γ collisions to form a pair cloud (e.g., Liang 1991) and subsequently blown away by radiation pressure (Sunyaev et al. 1992). The observed line width requires that the temperature of the annihilation site has to be $T < 3 \times 10^7$ K (2.5 keV) which implies that the observed annihilation photons do not come from the pair production region ($T > 10^9$ K; Liang & Dermer 1988). If the positrons annihilated in a cold dense cloud surrounding the pair production region, such a cloud would have to be either expanding or in a random motion with a velocity comparable to the Keplerian velocity to keep it from collapsing into the black hole within a few milliseconds. Doppler broadening of the line as a result of such motion would be as wide as >100 keV, contradictory to the observed narrow width. One would have to place the cloud far away from the black hole to make the line narrower, but then it would be hard to explain the observed line redshift. A natural way to be out of this dilemma is to consider the annihilation in an accretion disk. The accretion disk in XN Mus at the time near the annihilation epoch has a maximum temperature of 0.96 keV from *ROSAT* spectral fitting (Grenier 1992), so the thermal contribution to the line width is ≤36 keV. The Doppler broadening from the Keplerian rotation of the disk, on the other hand, will produce a maximum line width of ~120 keV. This is true even when the radiation comes from only part of the disk since the millisecond orbital period is far too short to be observed. To explain the observed narrow line width one needs only to assume that the accretion disk in XN Mus has a small inclination angle to our line of sight. Thus, since such disks usually lie in the orbital plane, the observed narrow annihilation line width of XN Mus provides a rare and unique opportunity to estimate the orbital inclination angle of the system (and so the mass of the black hole!).

The idea of positron annihilation in an accretion disk was first proposed by Ramaty et al. (1992) to explain the line observed in 1E 1740.7−2942 (see Fig. 1). There are many attractive features in this scheme. The high density and relatively low temperature of the inner region of the accretion disk make it an ideal place for the high-energy positrons intercepted by the disk to slow down and annihilate within a few r_S. This is consistent with the XN Mus line since the annihilation region has to be compact otherwise one would observe line broadening from the redshift distribution. Of course the disk may not be in a pure Keplerian circular motion especially during the X-ray outburst while material is transferred rapidly through the disk. But the radial velocity is usually small compared to the large Keplerian velocities (~10^5 km s^{-1}) and will not affect our results for the inclination angle. The tidal force of the secondary may also cause the outer part of the disk to deviate from a Keplerian circular motion, as indicated by the optical luminosity variation (Bailyn 1992), but it will have no noticeable impact on the inner region of the disk. There is actually evidence in γ-ray data that the annihilation in XN Mus takes place in an accretion disk. Gilfanov et al. (1991) report that the line shape may be more complicated than a simple Gaussian profile if the data are binned in the narrowest ($\Delta E \sim$ 15–20 keV) detector channels (see the inset graph in Fig. 1*a*). The line shape can be better described by *two narrow components* than by a single broad line. A double-peaked line profile is exactly what one would expect from the Doppler effect of Keplerian motion in an accretion disk (Chen & Halpern 1989; Bhattacharya & Gehrels 1991). The central dip in the profile may be caused by the radial inflow through the disk. Although the relatively poor statistics in the line and modest energy resolution do not allow a firm conclusion, we regard this as an important clue.

The reported annihilation line has an intrinsic FWHM = 58 ± 34 keV from Sunyaev et al. (1992), which is consistent to that reported by Goldwurm et al. (1992), 54 ± 54 keV. The rotational line broadening, $(\Delta E)_K$, is related to the

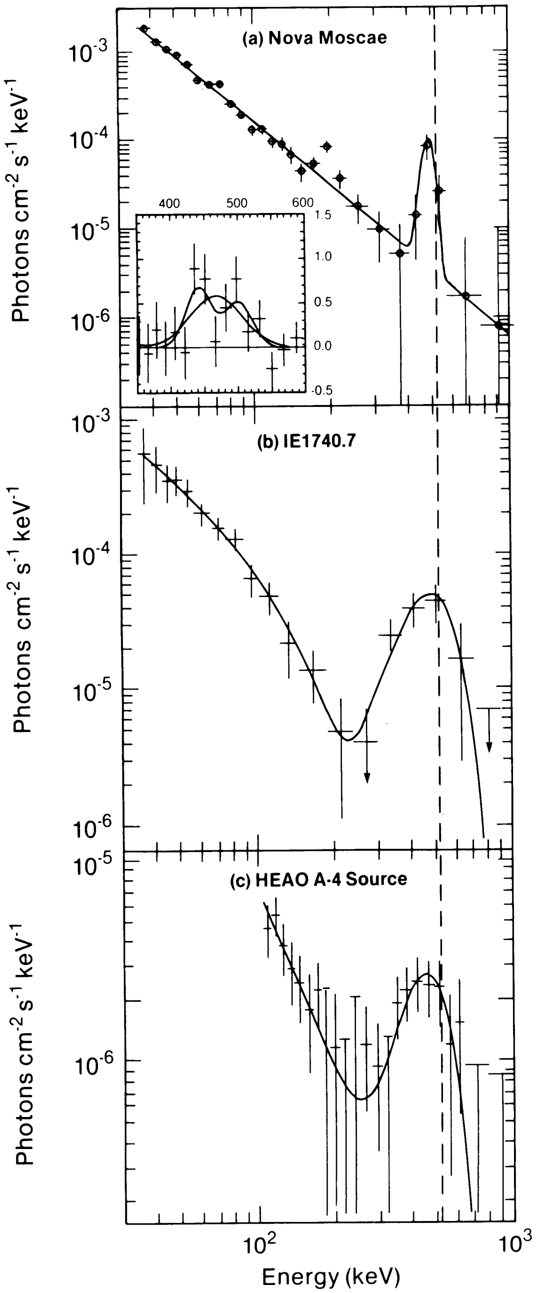

FIG. 1.—The photon spectra of the three known hard X-ray sources that have shown positron annihilation features. (*a*) X-ray Nova Muscae 1991 (from Goldwurm et al. 1992); (*b*) 1E 1740.7−2942 (from Bouchet et al. 1991); and (*c*) *HEAO* A-4 source (from Briggs 1991). The *solid* lines are the best-fit continuum plus a Gaussian annihilation profile. A *dashed* vertical line is drawn at 511 keV as a reference to show the redshift of the lines. The annihilation lines in both (*b*) and (*c*) are very broad which is consistent with thermal broadening or disk broadening at a large viewing angle (edge-on systems). The emission feature in XN Mus is considerably narrower, indicating a face-on system (see text). In (*a*), there is also a possible Compton reflection feature near 200 keV. The inset graph shows the SIGMA count spectrum of the annihilation feature after removing the power-law continuum (adopted from Gilfanov et al. 1991).

total intrinsic line width, ΔE, and the disk inclination angle by $\Delta E = [(\Delta E)_T^2 + (\Delta E)_K^2]^{1/2}$ and $(\Delta E)_K/E \sim v/c \cdot \sin\ i$, where $(\Delta E)_T = 37$ keV $(T/\mathrm{keV})^{1/2}$ is the thermal broadening, E is the redshifted line center energy, and $v/c = (GM/c^2 r)^{1/2} = (r_S/2r)^{1/2}$ is the Keplerian velocity at radius r. This gives $\sin i = (2r/r_S)^{1/2}(\Delta E)_K/E$, which can be used with equation (1) to calculate the mass of the compact primary, M, assuming a companion mass $M_c = 0.5 \pm 0.2\ M_\odot$. The results are listed in Table 1.

Because of the large uncertainties in the line widths, we cannot use the first-order error propagation method. Instead, we assume a Gaussian error distribution in the line width and calculate the mean and standard deviation of the derived parameters using exact formulae. Since both reported line widths allow arbitrarily small inclination angle, no upper limit on the black hole mass can be derived. The lower limits on the black hole mass listed in Table 1 are calculated from the largest inclination angle $\sin i + \Delta \sin i$.

Indirect evidence of a large black hole mass in XN Mus can also be obtained by modeling the broad band optical–to–hard X-ray spectrum. Using a standard thin accretion disk model Cheng et al. (1992) found a lower limit for the mass of the black hole of 12.5 $M_\odot$. However, we have included the *ROSAT* soft X-ray data and find that the simple thin blackbody disk model is no longer valid. Although the *ROSAT* spectrum by itself can be fitted by a thin disk model (Greiner et al. 1991), the observed soft X-ray flux is almost an order of magnitude less than the extrapolation from the UV spectrum obtained at the same epoch. On the other hand, the relatively large absorption column also allows the *ROSAT* spectrum to be equally well fitted by a power law (Greiner et al. 1991). In this case, if we require that the extrapolation of the UV disk emission to soft X-rays does not exceed the power-law flux, we get a lower limit on the black hole mass of $\sim 30\ M_\odot$. Further detailed modeling is underway.

3. DISCUSSION

Under the assumptions that (1) the annihilation line centroid redshift is purely gravitational and (2) the line width is caused by the combined effect of temperature broadening and disk rotation, we are able to estimate the orbital inclination angle of the XN Mus system and then to constrain the black hole mass. The major uncertainties in our results are due to the uncertaintes in the reported line widths. Because the line is narrow, the inclination angles are small and we conclude that the black hole mass is probably $> 8\ M_\odot$. The mass ratio in this binary system is also large, > 16 (assuming the companion mass of 0.5 $M_\odot$). This is the first time a γ-ray line has ever been used to determine the geometry of an accretion disk system, though the poor photon statistics in this data set introduces large uncertainties in the deduced black hole mass. This technique, however, can certainly be used in future, more sensitive γ-ray line observations such as those performed by the *Compton Gamma Ray Observatory* to achieve better precision.

An interesting complication to our interpretation is Compton scattering (Leventhal 1992). As the annihilation photons make their way out of the accretion disk, they can be Compton-backscattered to produce the 200 keV feature observed in the XN Mus spectrum. The forward-scattered photons will form a continuum (similar to that caused by the positronium three-photon annihilation) at energies below 511 keV (Lingenfelter & Hua 1991). When this continuum plus line are convolved with the finite detector energy resolution, the measured line can be redshifted and broadened (Leventhal 1973). However, the lack of positronium continuum below the line and the low value (<0.3) of the observed line flux ratio between the 200 and 480 keV features indicate a small Compton optical depth (Lingenfelter & Hua 1991) and thereby a small contribution to the annihilation line profile.

The distance to XN Mus is not well determined. Della Valle et al. (1991a) give an estimate of 1.4 kpc using optical data. Grebenev et al. (1991) confine it within $0.5 < D < 5$ kpc from ART-P data. Cheng et al. (1992) derive a large value of 8 kpc from the pre–nova companion brightness. The reported

TABLE 1

Annihilation Line Parameters and Derived Black Hole Mass

Parameters	Groups: Goldwurm et al.	Groups: Sunyaev et al.	Mean
Line center E (keV)	481 ± 22	476 ± 15	479 ± 18
Center redshift z	0.062 ± 0.049	0.074 ± 0.034	0.068 ± 0.042
Annihilation radius (r_S)	8.8 ± 6.2	7.6 ± 3.1	8.2 ± 4.6
Intrinsic FWHM (keV)	54 ± 54	58 ± 34	56 ± 44
Rotational FWHM[a] (keV)	48 ± 48	45 ± 37	46 ± 42
sin i	0.39 ± 0.40	0.37 ± 0.30	0.38 ± 0.35
Inclination angle i	28° ± 30°	24° ± 21°	26° ± 25°
Black hole mass ($M_{\odot}$):			
Lower limit (1 σ)	5	10	8

[a] After removing thermal broadening from the intrinsic width.

column density toward XN Mus from *ROSAT* observations (Greiner et al. 1991) is 1.45×10^{21} cm^{-2} which is consistent with the color excess $E(B-V) = 0.29$ measured with *IUE* and *HST* (Cheng et al. 1992). Using the empirical relationship between column density, Galactic latitude, and the distance above the Galactic plane (Diplas 1992), we find that XN Mus ($b = -7\overset{\circ}{.}1$) has reached the *maximum* absorption for that latitude and is at least 300–400 pc above the Galactic plane. This implies a *minimum* distance of 3 kpc and is fully consistent with 8 kpc. A nearby star, GS Mus, at the same Galactic latitude and having similar column density, has a distance of 5.2 kpc (Diplas 1992). The combined X-ray luminosity from both *ROSAT* and ART-P taken about 2 weeks after the hard X-ray continuum outburst is $\sim 1.3 \times 10^{38}$ ergs s^{-1} $(D/3\ \mathrm{kpc})^2$. If we require that the total X-ray luminosity at that time does not exceed 20% of the Eddington limit, as indicated by its hard X-ray luminosity evolution (Grebenev et al. 1991) and *ROSAT* spectral fitting (Greiner et al. 1991), the black hole mass is found to be $M \geq 4.5\ M_{\odot}\ (D/3\ \mathrm{kpc})^2$. If the distance is 8 kpc as suggested by Cheng et al. (1992), the lower limit is then 32 $M_{\odot}$.

The large mass of the black hole in XN Mus conjectured in this *Letter* may be pushing the current theoretical tolerance on the mass of a stellar-sized black hole and the mass ratio in a binary system. In the current massive star evolution model, the iron core mass at the end of the evolutionary track determines whether the final product becomes a black hole or not. If the core is greater than about 1.4 $M_{\odot}$, it will collapse into a black hole rather than form a neutron star. When this happens, the lack of a hard shell surface to bounce back the collapsing mass will prevent a massive supernova explosion and the whole remnant star can fall into the black hole in a more or less spherical fashion. Thus, one might expect that massive black holes are common since the main-sequence mass spectrum extends to above 100 $M_{\odot}$. The problem is that most theoretical models predict all massive stars of solar abundance go through a Wolf-Rayet phase during which mass loss is severe. The mass left at the end of the evolution becomes very small ($< 10\ M_{\odot}$) for almost the entire mass spectrum. The more massive a star is, the more severe its mass loss. So the most massive stars may not necessarily produce the most massive black holes. One way out of this dilemma is to let the star collapse before it enters the Wolf-Rayet stage, e.g., in the blue supergiant phase as in the case of SN 1987A. But how this is done for stars of solar abundance is still an open question. Another alternative is to produce a massive black hole through binary interaction. This is also directly related to our second problem of producing a close binary system of extreme mass ratio. A particularly interesting model (Eggleton & Verbunt 1986) has been proposed specifically for the black hole system A0620−00 in which a triple star system goes through two common envelope phases to form a black hole and a low mass close companion. This picture may be plausible if one considers that triple stars occur in as many as 15–20% of the stellar systems.

We are grateful to Jim Pringle, Mario Livio, Norbert Langer, and Carole Haswell for helpful conversations, and to Michael Briggs for permission to use a figure from his thesis and for useful conversations. We thank Athanaasios Diplas for providing the extinction curve and especially Marvin Leventhal for a critical reading of the manuscript. We appreciate useful suggestions by Josh Grindlay, Philipps Durouchoux, and the referee. F. H. C. is supported by NASA through grant number GO3232.01-91A, and the FY92 Director's Research Fund, from the Space Telescope Science Institute.

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