IONIZATION CONE IN THE X-RAY binary LMC X-1

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ABSTRACT

In an earlier paper, we presented the first evidence for a bow-shock nebula surrounding the X-ray binary LMC X-1 on a scale of ~15 pc, which we argued was powered by a jet associated with an accretion disk. We now present the first evidence for an ionization cone extending from an X-ray binary, a phenomenon only seen to date in active galactic nuclei (AGNs). The ionization cone, detected in the He ii λ4686/Hβ and [O iii] λ5007/ Hβ line ratio maps, aligns with the direction of the jet inferred from the bow-shock nebula. The cone has an opening angle ≈45° and radial extent ≈3.8 pc. Since the He ii emission cannot be explained by the companion O star, the gas in the ionization cone must be exposed to the “naked” accretion disk, thereby allowing us to place constraints on the unobservable ionizing spectrum. The energetics of the ionization cone give unambiguous evidence for an “ultraviolet-soft X-ray” (XUV) excess in LMC X-1. Any attempt to match the hard X-ray spectrum (>1 keV) with a conventional model of the accretion disk fails to account for this XUV component. We propose two likely sources for the observed anisotropy: (1) obscuration by a dusty torus, or (2) a jet-blown hole in a surrounding envelope of circumstellar absorbing material. We discuss the implications of our discovery in the context of the mass-scaling hypothesis for accretion onto black holes and suggest avenues for future research.

Subject headings: accretion, accretion disks — ISM: jets and outflows — techniques: spectroscopic — X-rays: binaries — X-rays: individual (LMC X-1)

1. INTRODUCTION

The search for a so-called unified model of AGNs has spanned more than two decades (Antonucci 1993). Indeed, it has been shown that some Type 2 Seyferts may comprise a Type 1 Seyfert nucleus that is heavily obscured by a dense, dusty torus (Lawrence & Elvis 1982; Antonucci & Miller 1985). Although dusty tori obscure some of the nuclear continuum emission, a significant fraction escapes along the poles of the central source, producing a cone-shaped extended emission-line region. Perhaps the most spectacular example occurs in the Type 2 Seyfert galaxy NGC 5252 where bipolar [O iii] cones are seen to extend to ~30 kpc in radius (Tadhunter & Tsvetanov 1989). This important phenomenon allows one to test the unified model by analyzing the ionization properties of the gas within the cones.

Many of the phenomena we observe from active galaxies arise from the properties of the accretion disk. Edelson & Nandra (1999) note that the power density spectrum of an active galaxy resembles those observed in some Galactic black hole X-ray binaries (XRBs), such as Cyg X-1 (see also McHardy 1989). The transient behavior of XRBs, however, may render “the scaling from stellar-to-supermassive black hole mass” a false argument (Done & Gierliński 2005). But if appropriate corrections are made for the variations in the accretion rate, the variability timescales may be related (McHardy et al. 2006).

If the mass-scaling hypothesis for black holes is correct, it is natural to question why we have not observed ionization cones associated with XRBs in previous work. This may reflect the difficulty of interpreting the complex nebulousity in the vicinity of XRBs due to a background of competing sources, e.g., hot young stars. The XRB LMC X-1 is surrounded by a complex filamentary emission-line nebula, catalogued by Henize (1956) as N159F. The X-ray source \( L_x(2–10 \text{ keV}) \approx 2 \times 10^{38} \text{ erg s}^{-1} \); Schlegel et al. 1994] comprises a stellar-mass (4–10 \( M_\odot \)) black hole accreting matter from an O7 III–type star (“star 32”). Based on the He ii λ4686 emission line, Pakull & Angebault (1986) demonstrated that N159F was the first example of an X-ray ionized nebula. Ramsey et al. (2006) supported the presence of an X-ray ionized nebula, and concluded that LMC X-1 “is not injecting a significant amount of mechanical energy into the interstellar medium,” contrary to the findings of Cooke et al. (2007) (hereafter Paper I), who recently suggested that the nebula surrounding LMC X-1 is largely driven by a jet emanating from the XRB. The latter study used integral field spectroscopy (IFS) to delineate the complex ionization regions within the nebula. The two studies prior to Paper I used 1D slit spectroscopy, a technique that is spatially more limited than IFS.

Once again we appeal to IFS to obtain complete spatial coverage of the nebula. The motivation behind our new study is to assess the extent of hard ionizing photons by tracing the He ii and [O iii] emission. In the course of our work, we have discovered an ionization cone associated with this XRB, the first of its kind. Moreover, the ionization cone aligns with the putative jet from Paper I, a phenomenon also observed in AGNs (Unger et al. 1987). Not only does this provide a new ground for testing accretion disk phenomena, but it also strengthens the mass-scaling hypothesis, implying that accretion processes around stellar-mass black holes are similar to accretion processes around supermassive black holes.

We summarize the observations and data reduction procedures in § 2. In § 3, we derive the cone parameters and discuss the ionizing source. Our interpretation and conclusions are summarized in § 4.

2. OBSERVATIONS

After presenting our previous results on LMC X-1 (Paper I), we were alerted to archival Visible Multi-Object Spectrograph (VIMOS) IFS observations (program ID: 076.C-0284(B)) of N159F, which were acquired in 1.4”–1.6” seeing...
on 2005 October 1 and 27. Four 900 s VIMOS exposures were taken in high-resolution mode, two using the blue grism ($R \approx 2050, 4150–6200$ Å) and two using the orange grism ($R \approx 2150, 5200–7600$ Å). The spectral range includes the prominent optical emission lines [O i], [O iii], H i, He i, He ii, [Ar iii], [N ii], [S ii], Hß, and Hα, all of which are important diagnostics for delineating regions containing multiple ionizing sources, and estimating the electron density and temperature. The two exposures with each grism were offset east-west by 12.7′′ (19 pixels) and north-south by 3.4′′ (5 pixels).

The data were reduced using the reduction pipeline VIPGI† (Scodeggio et al. 2005). The reduced data were converted into 3D datacubes and combined using the same data manipulation routines implemented in Paper I. At the spectral resolution of the VIMOS grisms, all lines were found to be well approximated by a single unresolved Gaussian profile.

3. RESULTS

3.1. Morphology and Ionization Source

Figure 1a immediately highlights the anisotropy of He ii emission and its correlation with the [O iii] emission (see Paper I), which is the first evidence that isotropic ionization by LMC X-1 is unlikely. An ionization cone is revealed when taking the ratio of these high ionization emission lines with respect to Hß (see Figs. 1b and 1c), as these line ratios are strongly dependent on the ratio of the ionizing photon intensity and the gas density (i.e., ionization parameter) at a fixed gas abundance. Jets, winds, and cones are often asymmetric and this may arise from the source or be due to large-scale dust or the presence of gas. The one-sided cone, we measure its position angle, half-opening angle, and orientation are clearly defined (Mulchaey et al. 1996). For our inferred and pc, the ionization cone is optically thick to H0 Lyman continuum photons $[\lambda(\text{He }^+), h\nu = 13.6 \text{ eV}]$ and He$^+$ Lyman continuum photons $[\lambda(\text{He }^+), h\nu = 54.4 \text{ eV}]$. However, the ionization cone is optically thin to photons above $\epsilon_\nu = 250–300 \text{ eV}$ (Yan et al. 1998).

We now use the observed X-ray spectrum to derive our first estimate of the ionizing flux from LMC X-1. The X-ray spectrum is best fitted by a Comptonized multicolor disk (CMCD) model (Yao et al. 2005). However, for energies $\leq 1 \text{ keV}$, the X-ray spectrum of LMC X-1 can be approximated by the simple multicolor disk (MCD) model (Fig. 2, Yao et al. 2005). The

† VIPGI-VIMOS Interactive Pipeline Graphical Interface, obtained from http://cosmos.iasf-milano.inaf.it/pandora/.
MCD model presented in Figure 2 adopts the following parameters: $k T_{in} = 0.93$ keV and $K_{MCD} = 57$, where $T_{in}$ is the inner disk temperature, and $K_{MCD}$ is a normalizing constant. We present this model with and without line-of-sight attenuation ($N_{H}$).

Since $K_{MCD}$ depends on the assumed inclination angle $i$, we set $i = 0$ to determine the ionizing luminosity within the cone. We determine the absorption-corrected photon flux from 13.6 eV to $\epsilon_e = 300$ eV and 54.4 eV to $\epsilon_e = 300$ eV along our line of sight to be $\mathcal{F}_{i}(\lambda 4686)_{X} \approx 0.6$ photons cm$^{-2}$ s$^{-1}$ and $\mathcal{F}_{i}(\text{He}^+)_{X} \approx 0.4$ photons cm$^{-2}$ s$^{-1}$, respectively. Therefore the number of H$^+$ and He$^+$ Lyman continuum photons in the cone produced by the X-ray source is

\begin{equation}
\mathcal{N}_{i}(\text{H}^+)_{X} = \Omega D^2 \mathcal{F}_{i}(\text{H}^+)_{X} \approx 8 \times 10^{45} \text{ photons s}^{-1},
\end{equation}

\begin{equation}
\mathcal{N}_{i}(\text{He}^+)_{X} = \Omega D^2 \mathcal{F}_{i}(\text{He}^+)_{X} \approx 6 \times 10^{45} \text{ photons s}^{-1},
\end{equation}

at the distance ($D \approx 55$ kpc; Feast 1999) to the LMC. The subscript “X” indicates that these estimates were obtained from an extrapolation of the X-ray model.

From the VIMOS data, we measure the extinction corrected He II $\lambda 4686$ flux of the cone to be $F_i(\lambda 4686) \approx 10^{-17}$ erg cm$^{-2}$ s$^{-1}$ [$(B-V) = 0.37$; Bianchi & Pakull 1985] corresponding to a cone luminosity $L_i(\lambda 4686) \approx 4 \times 10^{34}$ erg s$^{-1}$. If we assume case B recombination, from the ratio of the total to effective recombination coefficients, $\alpha(\text{He}^+, T)/\alpha_{\text{eff}}(\lambda 4686)(T) = 4.2$ (for $T = 10^4$ K; Péquignot et al. 1991), we estimate (eq. [41], Harman & Seaton 1966)

\begin{equation}
\mathcal{N}_{i}(\text{He}^+) = \frac{L_i(\lambda 4686)}{h \nu_{4686}} \frac{\alpha(\text{He}^+, T)}{\alpha_{\text{eff}}(\lambda 4686)(T)} \approx 4 \times 10^{46} \text{ photons s}^{-1},
\end{equation}

power the cone, where $h \nu_{4686} = 2.6$ eV. This estimate would be higher still if the covering factor of the gas in the ionization cone was less than unity.

Considering the well-established metal deficiency of the LMC ($\sim \frac{1}{2}$ solar), if star 32 were solely responsible for the ionization cone, its stellar temperature would need to be in excess of 50000 K (Evans & Dopita 1985), which is inconsistent with the known value, $T_{\text{eff}} = 37000$ K (Bianchi & Pakull 1985). However, star 32 is capable of producing photons with energies $\sim 54.4$ eV, and assuming it radiates isotropically, it will produce $\mathcal{N}(\text{He}^+) \approx 6 \times 10^{46}$ photons s$^{-1}$ (Vacca et al. 1996). Therefore star 32 produces insufficient He$^+$ Lyman continuum photons to explain the observed ionization cone.

We now derive a new estimate of $\mathcal{N}_{i}(\text{H}^0)$ that is independent of the extrapolation from the X-ray spectrum. The [O III] $\lambda 5007$/[O II] $\lambda 3726$ ratio in the cone provides us with a direct determination of the ionization parameter $q$ for a gas with known metallicity (Kewley & Dopita 2002). Due to the insufficient spectral coverage of the VIMOS blue grism, the [O III] lines are not present in the VIMOS datacube. Instead, we use the [O III]/[O II] ratio (≈1.9) determined from “position 1” (Pakull & Angebault 1986). For the LMC gas phase abundance, this ratio corresponds to a unique ionization parameter $q_i \approx 7 \times 10^7$ cm s$^{-1}$ (Kewley & Dopita 2002) due to the differential dependence of oxygen ions on the ionization rate. Thus

\begin{equation}
\mathcal{N}_{i}(\text{H}^0) = \Omega r^2 q_i n_e \approx 8 \times 10^{46} \text{ photons s}^{-1},
\end{equation}

where $r$ is the characteristic radius of the cone ($r/2$). Outside the cone, there is a decrease in $q$ at increasing radius from LMC X-1. For example, the [O III]/[O II] ratio at a distance of 1.3′ (~20 pc) northeast of LMC X-1 (“position 2,” Pakull & Angebault 1986) is indicative of an ionization parameter $q_i \approx 2 \times 10^7$ cm s$^{-1}$.

4. DISCUSSION

By comparing equations (1)–(4), the Yao model underestimates the number of ionizing photons emerging from the accretion disk by a factor of 7–10. This discrepancy requires an additional component that dominates in the UV and/or soft X-ray bands. In the Yao model, we cannot increase $K_{MCD}$ because it is constrained beyond 1 keV by the observed hard X-ray spectrum (see Fig. 2), which is modeled as Comptonized disk emission. We note that the size of the discrepancy arising from equations (1)–(4) is exaggerated by the use of a photon number; the energy requirement is only a factor of 2 more than the Yao model. This could conceivably arise from upscattering of lower energy photons from more distant regions in the disk by a hot coronal plasma in the inner region. Alternatively, a sizeable fraction of the hard X-ray photons could be degraded to lower energies, i.e., in the opposite sense to what is assumed in the CMCD model. It is noteworthy that some AGN ionization cones can only be explained by the contribution of both ionization from the nonstellar nuclear continuum and jet-induced shock ionization (Pogge 1988; Wilson et al. 1988). Therefore an in situ jet may also contribute to the LMC X-1 cone, although the nebular temperature limits any contribution from shock processes.

EUV/soft X-ray excesses are not uncommon to AGNs. The spectra of high-redshift quasars, which can be observed in the UV, clearly exhibit a big blue bump component, widely attrib-
uted to accretion disk emission (Sanders et al. 1989). This component has also been inferred from the emission-line diagnostics of Seyfert 2 ionization cones (Alexander et al. 2000). In some cases, EUV/soft X-ray excesses are also observed. The origin of this component is unclear, but it may arise, for example, from thermal emission in a warm/hot cloud at a temperature that peaks in the 30–300 eV range (Siemiginowska et al. 1995). How this component relates to the accretion disk is not clear.

It is unlikely that the angular extent of the ionization cone reflects the poloidal ionizing field of the naked accretion disk. There are two plausible explanations for the anisotropic radiation pattern: (1) obscuration by a dusty torus, or (2) a jet-blown hole in the envelope of circumstellar absorbing material (Kuulkers 2005; Nespoli et al. 2008).

We suspect that obscuring XRB tori would scale to AGN tori with the mass accretion rate rather than the black hole mass. The mass accretion rate in XRBs depends on the donor star, whereas for AGNs, it depends on the gas fuel supply from the surrounding interstellar medium. Because star 32 is a giant, we would expect an excess mass flux to accumulate somewhere before reaching the accretion disk. This accumulated mass flux could form something akin to an obscuring torus. By analogy with AGNs (Pier & Krolik 1993), high angular resolution, mid-infrared observations of LMC X-1 are required to confirm the presence of a dusty torus.

Here we have demonstrated the importance of ionization cones for establishing the XUV properties of obscured accretion disks. We suspect the ionization cone will also be observable in [Ne III] X3868 and [Ne V] X3426 (ionization potential 63.5 and 126.2 eV respectively). These arise at higher q values and will therefore allow us to probe down to smaller radii. Indeed, Pakull & Angebault (1986) have already detected these two high ionization species in the immediate vicinity of LMC X-1. But due to the limited spatial coverage of their spectroscopic technique, we are unable to confirm that these ratios are enhanced in the direction of the ionization cone. Planned future observations will probe the structure of the ionization cone, allowing us to refine our ionization model and place tighter constraints on the nature of the ionizing source.

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