SPECTACULAR TRAILING STREAMERS NEAR LMC X-1: THE FIRST EVIDENCE OF A JET?

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ABSTRACT

We report VIMOS integral field spectroscopy of the N159F nebula surrounding LMC X-1. Our observations reveal a rich, extended system of emission-line filaments lining the boundary of a large conical cavity identified in Spitzer mid-IR imaging. We find that X-ray photoionization cannot be solely responsible for the observed ionization structure of N159F. We propose that the extended filamentary emission is produced primarily by ionization from a shock driven by a presently unobserved jet from LMC X-1. We infer a shock velocity of \( v_s \approx 90 \text{ km s}^{-1} \) and conclude that the jet responsible for the bow shock is presently undetected because it has switched off, rather than because it has a low surface brightness. This interpretation is consistent with the present soft X-ray spectral state of LMC X-1 and suggests the jet is intermittent.

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

1. INTRODUCTION

LMC X-1 resides in the highly complex nebula region N159 (Henize 1956). It is the most powerful known X-ray source in the LMC (Johnston et al. 1979), with an X-ray luminosity \( L_X \approx 2 \times 10^{39} \text{ erg s}^{-1} \) (Schlegel et al. 1994), and is believed to be powered by accretion onto a stellar mass (4–10 \( M_\odot \)) black hole with a companion O7 III type star identified as star 32 (Pakull & Angebault 1986; Cowley 1992). Pakull & Angebault (1986) collated extensive spectral data and ruled out collisional excitation by a supernova remnant. They concluded that their detection of He ii emission is the first evidence for an X-ray-ionized nebula (see also Ramsey et al. 2006). We note, however, that the slit spectra used in these studies were limited to a relatively localized region of the nebula, in the immediate vicinity of LMC X-1.

Using integral field spectroscopy (IFS), we present new evidence suggesting that X-ray photoionization cannot be solely responsible for the observed large-scale morphology and high-excitation lines, which we propose are best understood in terms of shock ionization attributable to an as yet undetected relativistic jet from LMC X-1. Indeed, the highly complex ionization structure of the extended nebula surrounding LMC X-1 is strikingly reminiscent of the other two only known examples of jet-induced shock-ionized nebulae, those surrounding the powerful Galactic X-ray binaries SS 433 (Dubner et al. 1998) and Cygnus X-1 (Gallo et al. 2005).

We were initially alerted to the possibility of shock ionization in N159F after observing with the Taurus Tunable Filter (TTF) at the Anglo-Australian Telescope (Bland-Hawthorn & Jones 1998) in 2003 December. We discovered a rich system of streaming \( \text{H} \alpha \) filaments in the arcminute-scale nebula. The filaments trail back from the apex of a conical cavity in the dust emission seen in the Spitzer Infrared Array Camera (IRAC) image of Jones et al. (2005). The apex is positioned \( \approx 12\ arcmin \) southwest of LMC X-1, corresponding to \( \approx 3.2 \) pc at a distance \( d \approx 55 \text{ kpc} \) to the LMC (Feast 1999).

Motivated by these observations, we undertook further investigation into the environment of LMC X-1 through IFS with VIMOS at the Very Large Telescope (VLT) in 2005 November.

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The new data reveal strong detections of optical emission lines due to [O i], [N ii], [S ii], He i, and [Ar iii], as well as \( \text{H} \alpha \). The emission lines all show a morphological bow shock structure similar to the initial \( \text{H} \alpha \) filamentary streamers seen in the TTF image. In Figure 3 of Jones et al. (2005), which overlays the 5 GHz radio contours of Hunt & Whiteoak (1994) on an IR image of N159, radio emission appears to trace the IRAC cavity.

We summarize the observations and data reduction procedures in § 2. In § 3 we present our results and provide an interpretation of the environment of LMC X-1. Our conclusions are summarized in § 4.

2. OBSERVATIONS AND DATA ANALYSIS

Our initial TTF observations of the N159F nebula were taken in a 5 Å bandpass centered on \( \text{H} \alpha \). A powerful differential technique called “straddle shuffling” (Maloney & Bland-Hawthorn 2001) was used to remove the surrounding continuum emission to better than 1% accuracy, revealing the filamentary structure of the nebula. These data prompted observations with the VIMOS integral field unit (IFU) at the VLT on 2005 November 2, 5, and 6. Conditions were reported as photometric, with 1.4–1.5” seeing (well matched to the 0.67” spatial scale of the IFU). Observations were queue scheduled using the HR-Orange grating (\( R \approx 2500, 5250–7400 \) Å) and include the emission lines \( \text{H} \alpha, [\text{O} \ i],[\text{N} \ ii],[\text{S} \ ii], \text{He} \ i, \) and [Ar iii]). The systemic radial velocity \( (v_s \approx 270 \text{ km s}^{-1}) \) of the LMC ensures that the [O i] and \( \text{H} \alpha \) emission lines are well separated from their telluric counterparts.

Given the \( 27” \times 27” \) field of view of the VIMOS IFU in high-resolution mode, four VIMOS pointings were required (with a 5 pixel/3.3” overlap) to tile the \( \text{H} \alpha \) filaments along the boundaries of the mid-IR cavity in the vicinity of LMC X-1. Three 1160 s exposures were taken at each of the four pointings. The data were reduced using the reduction pipeline VIPGI\(^1\) (see Scodeglio et al. 2005 for details). Data cubes were created and subsections of the final mosaic were combined using a set of IFU data manipulation routines created in IDL. Emission-line fitting was performed for each prominent spectral line using a single unresolved Gaussian profile.

Due to the restricted spectral coverage of the chosen VIMOS

\(^1\) VIPGI (VIMOS Interactive Pipeline Graphical Interface) can be obtained from http://cosmos.iasf-milano.inaf.it/pandora.
setting, the key shock diagnostic line [O iii] λ5007 is not present in our data. However, we retrieved archival [O iii] observations from the public ESO archive. The 2.3 m WFI observations\(^4\) of N159F consists of 2 × 500 s observations using the [O iii] filter and 2 × 125 s observations using the R\(_c\) filter. The data were processed in the usual manner (overscan-corrected, flat-fielded from twilight flat frames, aligned, and combined) using elements of the CASU imaging processing toolkit (Irwin & Lewis 2001). Continuum subtraction was achieved for the [O iii] and Hα narrowband images using the aligned and scaled V and R\(_c\) images, respectively. The WFI and VIMOS data were spatially registered and resampled using stellar images common to both data sets.

3. RESULTS AND DISCUSSION

Figure 1 shows the main results from the new VIMOS, WFI, and IRAC observations. Together, these provide compelling evidence for shock ionization in the N159F nebula surrounding LMC X-1. The four top left panels of Figure 1 show the prominent emission lines H\(_\alpha\), [Ar iii], and [O i] in the VIMOS data cube, and [O iii] from the continuum-subtracted WFI data. A bow shock morphology, with trailing filaments, is evident in the images. The first of the top right panels shows a line diagnostics plot formed from a pixel-pixel comparison of [O iii]/[O i] versus [Ar iii]/[S ii], where four color-coded ionization regions show spatial coherence over the N159F nebula (see the panel to the right of the scatter plot). Also shown among the top right panels is a three-color Spitzer IRAC image centered on star 32 (Jones et al. 2005), showing a dust cavity associated with the proposed bow shock. Among the four panels on the bottom left, the lower left one presents a three-color composite image in [N ii] (red), H\(_\alpha\) (green) and [O i] (blue). We speculate that the shock is driven by a jet, with the orientation indicated in this panel.

3.1. Disentangling the Shock-ionized Nebula

Separating out the shock-ionized part of the optical nebula is not straightforward, as radiative shocks can produce collisionally excited optical emission lines similar to those produced by X-ray photoionization (see, e.g., Dopita & Sutherland 2003). Both ionization mechanisms can produce enhanced (relative to H\(_\alpha\) regions) H\(_\alpha\) as well as enhanced forbidden lines of neutral or low-ionization species, such as [O i] λ6300, [S ii] λλ6716, 6731, and [N ii] λλ5548, 5563, and of higher ionization species, such as [O iii] λλ5007, 4959 and [Ar iii] λ7136. He \(_\Pi\) λ4686 is a reliable X-ray photoionization diagnostic, as it is difficult to produce with shock ionization, while [Ar iii] is difficult to produce with X-ray photoionization, except for very high ionization parameters (R. Sutherland 2007, private communication). Furthermore, X-ray photoionization tends to favor the production of [O iii] over [O i] (Draine & McKee 1993). On the other hand, [O iii] can be a powerful shock diagnostic, since all radiative shock models (Cox & Raymond 1985; Binette et al. 1985; Hartigan et al. 1987) consistently predict a dramatic onset of [O iii] emission near a critical shock speed, \(v_\text{c} \approx 100 \text{ km s}^{-1}\).

While the H\(_\alpha\) and [Ar iii] images on the top left in Figure 1 exhibit a similar morphological structure suggestive of a bow shock, a comparison of the [O i] and [O iii] images shows regions of anticorrelation in the immediate vicinity of LMC X-1 and around the B5 I star R148 (Feast et al. 1960), where there is a deficit of [O i] emission but enhanced [O iii] emission. R148 is not capable of producing this high-excitation emission. Indeed, its Strömgren sphere (\(r \approx 0.04 \text{ pc}\)) does not even encompass one pixel of our image. The Strömgren radius for star 32 (the O7 III companion to LMC X-1; Cui et al. 2002) is \(= 0.9 \text{ pc}\), comparable to the size of the blue region defined in the upper top right panels. Recalling that X-ray photoionization favors [O iii] over [O i] and can produce [Ar iii] for high-ionization parameters, this blue region, which exhibits the largest local enhancement in [O iii]/[O i] and [Ar iii]/[S ii] must be due to the combined effects of X-ray ionization by LMC X-1 and photoionization by star 32. The yellow region in the upper top right panels is consistent with the extent of the X-ray Strömgren radius (≈ 2 pc), calculated by Pakull & Angebault (1986).

Note, however, that this yellow region is located to the east (left) of R148, on the far side of LMC X-1, and spatially coincides with some of the streamers. Thus, we interpret the yellow zone of enhanced [Ar iii]/[S ii] and [O iii]/[O i] as being due to a combination of shock ionization and X-ray ionization. The red zone in the upper top right panels is predominantly shock-ionized. The upper panels on the bottom left show a proposed trail of streamers through this shock-ionized region.

The evidence for X-ray photoionization in N159F has hitherto been based on slit spectra of He \(_\Pi\) λ4686 emission detected in the immediate vicinity of LMC X-1 (Pakull & Angebault 1986; Ramsey et al. 2006). In the lower right panel of the bottom left set, we show the positioning of the echelle slits used by Ramsey et al. (2006) to detect the He \(_\Pi\) emission. Pakull & Angebault (1986) used similarly placed orthogonal slits, but centered on star 32 instead of R148. Note that although the echelle slits coincide with the yellow zone we identify as being both shock ionized and X-ray ionized, the observed He \(_\Pi\) λ4686 emission is almost certainly due to only X-ray ionization as none of the radiative shock models predict significant He \(_\Pi\) λ4686. Note also that it would have been extremely difficult to find unequivocal evidence for shock ionization from other line diagnostics due to the confusion with X-ray ionization in this region and also to the spatially limited extent of the slits. On scales of several parsecs, our IFU data reveal enhanced [O i]/H\(_\alpha\), [O iii], and [Ar iii], as well as H\(_\alpha\), forming a shell-like structure around LMC X-1, but extending beyond the X-ray Strömgren radius (that is, beyond the yellow zone in the upper top right panels of Fig. 1). This is compelling evidence that shock ionization rather than X-ray ionization is primarily responsible for this high-excitation emission seen on the largest scales in the nebula.

3.2. Physical Parameters

The electron density panel of Figure 1 shows an image of the electron number density, \(N_e\), deduced from the [S ii] emission (Osterbrock & Ferland 2006). It reveals an enhanced flattened region that falls slightly inside and near the apex of the bow shock morphology. This structure is highly suggestive of a “Mach disk” commonly seen in bow shocks associated with Herbig-Haro jets (Hartigan et al. 1999). In the flattened region, we find \(N_e \approx 1600 \text{ cm}^{-3}\), a factor \(\approx 3\) times greater than the environment. This is less than the maximum compression ratio of 4 expected for a strong shock, but is compatible with the Mach number inferred from the shock speed (see below).

From the high-density region, we can determine a shock speed using the multitude of line ratios extracted from a single IFS exposure. The bottom right panel of Figure 1 shows theoretical line ratios from the radiative shock model of Hartigan et al. (1987). The dashed horizontal lines indicate the maximum and minimum shock speeds obtained from the new data for...
Fig. 1.—The four top left panels are continuum-subtracted integrated line flux images of N159F in Hα, [Ar III], [O I], and [O III]; filled blue circles indicate the locations of stars 32 (right) and R148 (left); north is up and east is to the left (5′ ≈ 1.3 pc). The first of the top right panels shows a diagnostic scatter plot of [O III] λ5007/λ6300 vs. [Ar III] λ7136/λ6716+6731; the color coding corresponds to different ionization regions shown in the following panel. Below is an electron density image, showing an arc of higher electron density to the south, and to the right of that is a Spitzer three-color composite image of N159F (Jones et al. 2005), constructed from the IRAC 3.6, 4.5, and 8.0 μm bands. The upper panels on the bottom left show Hα and [O III]/[O I] images overlaid with a proposed trail of the streamer filaments. Below the Hα panel is a false-color image (red, green, blue = [N II] λ6583, Hα, [O I] λ6300), with the proposed bow shock and jet orientation indicated. The panel to the right of this is the same as the far top right panel, with overlaid blue lines indicating the echelle slit positions of Ramsey et al. (2006); gray lines are the proposed streamers. The bottom right panel shows the predicted line ratios and corresponding shock speeds from the radiative shock model in Hartigan et al. (1987) (solid curves) overplotted with observed ranges of line ratios (dashed lines) measured from the region of high electron density shown in the electron density panel.

Each corresponding line ratio. From the presence of [O III], we infer a lower limit \( v_s \approx 80 \text{ km s}^{-1} \). [Ar III]/He I suggests \( v_s \approx 190 \text{ km s}^{-1} \), while both the [S II]/Hα and [Ar III]/Hα line ratios further constrain the shock velocity to \( v_s \approx 90–100 \text{ km s}^{-1} \). Thus, we estimate a shock speed \( v_s \approx 90 \text{ km s}^{-1} \), as indicated by the black dashed vertical line in the bottom right panel. This is broadly consistent with the line profiles being marginally resolved at \( \approx 120–150 \text{ km s}^{-1} \) FWHM within the high-density region. It also implies a Mach number of \( \approx 6 \), assuming an isothermal sound speed \( \approx 14 \text{ km s}^{-1} \) for an ambient
gas temperature of $10^4$ K. We note, however, that the deduced value of $v_e$ is likely to be somewhat overestimated, as the Hartigan et al. (1987) shock model assumes a neutral preshock medium, and this produces a spectrum similar to preionized, shocked material with a lower $v_e$ (Cox & Raymond 1985).

### 3.3. Energy Budget

The streamers are unlike the uniform wind-blown bow shocks associated with OB-runaway stars (see, e.g., Kaper et al. 1997). Indeed, the inferred space velocity $v_e$ of the O7 III companion is too low to be consistent with this interpretation. We estimate $v_e \approx 0.4M/M_{10^{-7}} M_\odot yr^{-1} L_{1500}^{1/2} \left(\rho M_{10^{-22}} g cm^{-3} \right)^{-1/2} R_{1500}^{1/2}$ km s$^{-1}$ (Kaper et al. 1997), where $v_e = 1500L_{1500}$ and $M_\odot$ are the wind velocity and mass-loss rates of star 32 (Pakull & Angebault 1986). $\rho$ is the mass density of the ambient medium, deduced from the [S ii] lines ($\S$ 3.2), using an ionization fraction of $x \approx 1$, and $R = 3.2R_{1500}$ is the distance between star 32 and the stagnation point (apex), which has an angular distance $12''$ corresponding to $\geq 3.2$ pc, where the inequality takes into account projection effects. We henceforth consider the possibility that the shock is produced by a jet from LMC X-1.

Adopting the “dentist drill” model of Scheuer (1974), a cavity, or cocoon, develops naturally around a jet plowing through the ambient ISM. A shock develops around the cocoon and the shocked gas then comes into dynamical (ram) pressure equilibrium with the jet. Thus, $\rho v_e^3 \approx \rho_0 v_0^3$, where $\rho_0$ and $v_0$ are the mass densities of the jet and shocked gas, respectively, and $v_0$ and $v_e$ are the corresponding speeds. The total jet kinetic power is

$P_0 = \pi \rho_0 v_0^3 (\theta/2 \times 10^{-21} g cm^{-3})$ ergs s$^{-1}$. Here, $\phi_0 = \phi/10^\circ$ (Miller-Jones et al. [2006] find an upper limit of $\phi \leq 10^\circ$ for X-ray binary jets), $\theta/2 \times 10^{-21} g cm^{-3}$, and $\phi$ is the jet inclination angle to our line-of-sight. We have used a postshock electron number density $N_e = 1.6 \times 10^3$ cm$^{-3}$ ($\S$ 3.2) to estimate $\rho_0$. This estimate of jet power falls squarely within the range $P_0 \approx 0.03$ Myr from Fender & Pooley (2000) for quasi-steady X-ray binary jets.

It is noteworthy, however, that LMC X-1 currently appears to be in a persistent high/soft X-ray spectral state (Schlegel et al. 1994), during which it is unlikely to be producing a powerful jet (Fender et al. 2004) and its X-ray luminosity is dominated by the accretion disk, which radiates away all the accretion power. Since the accretion power inferred from the observed X-ray luminosity, $\approx 2 \times 10^{34}$ ergs s$^{-1}$, is an order of magnitude less than the inferred jet power, we suggest that rather than being a dark jet (as Gallo et al. [2005] proposed for Cyg X-1, which is in a low/hard spectral state), the nondetection of the LMC X-1 jet results from the inherent transient nature of X-ray binary jets. The jet is not presently seen because it may have recently switched off and the shock-ionized nebula surrounding LMC X-1 is still radiating the energy impacted during an earlier jet-active epoch. We estimate a radiative cooling timescale of just $\approx 10^3$ yr, assuming 0.3 solar metallicity (Dopita & Sutherland 2003). The jet-active phase may have been triggered by a relatively sudden increase in the mass accretion rate, which has a present value $M_\dot{\equiv} \approx 12L_{1500} c^2 \approx 4 \times 10^{-8} M_\odot yr^{-1}$ (assuming a radiative efficiency of 1/12 for standard thin-disk accretion). The dynamical timescale over which the jet-driven shock has been expanding into the ISM is estimated as $t_\text{dyn} \approx 3.2$ Myr, which is remarkably similar to jet lifetime estimates obtained for other X-ray binaries (Gallo et al. 2005; Kaiser et al. 2004).

### 4. Conclusions

We have demonstrated the extraordinary power of integral field spectroscopy in our study of the emission-line nebula N159F around LMC X-1. Different emission-line diagnostics have been combined to separate out different ionization regions on extended scales. We propose that three ionizing sources contribute to the complex nature of N159F: (1) photoionization by star 32 (the O7 III companion to LMC X-1), (2) X-ray photoionization by LMC X-1 itself, and (3) jet-driven shock ionization. The first two phenomena are relatively localized, whereas shock ionization dominates over the extended streamers, which appear to be bounded by a bow shock morphology. The morphology and ionization properties of the extended nebula around LMC X-1 are strikingly similar to those seen in other known jet-driven shock-ionized nebulae around Galactic X-ray binaries. We infer a shock speed of $v_e \approx 90$ km s$^{-1}$ and deduce the power of the jet driving the shock to be $\approx 2 \times 10^{39}$ ergs s$^{-1}$. Since LMC X-1 is unlikely to be producing a jet in its current X-ray spectral state, we propose that the jet is intermittent, with a characteristic lifetime of $\approx 0.03$ Myr.

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