THE ASTROPHYSICS OF THE ASYMPTOTIC GIANT BRANCH STAR IRC+10216

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ABSTRACT

We have discovered a very extended shock structure (i.e., with a diameter of about 24′) surrounding the well-known carbon star IRC+10216 in ultraviolet images taken with the Galaxy Evolution Explorer satellite. We conclude that this structure results from the interaction of IRC+10216’s molecular wind with the interstellar medium (ISM), as it moves through the latter. All important structural features expected from theoretical models of such interactions are identified: the termination shock, the astrosheath, the astropause, the bow shock, and an astrotail (with vortices). The extent of the astropause provides new lower limits to the envelope age (69,000 years) and mass (1.4 $M_\odot$, for a mass-loss rate of $2 \times 10^{-5} M_\odot$ yr$^{-1}$). From the termination-shock standoff distance, we find that IRC+10216 is moving at a speed of about $\gtrsim$91 km s$^{-1}$ (1 cm$^{-3}/n_{\text{ISM}}^{1/2}$ through the surrounding ISM.

Key words: circumstellar matter – dust: extinction – ISM: structure – stars: AGB and post-AGB – stars: individual (IRC+10216) – stars: mass-loss

1. INTRODUCTION

The carbon-rich star IRC+10216 is the closest ($D \sim 120$–150 pc) asymptotic giant branch (AGB) star with a high mass-loss rate ($M \sim 2 \times 10^{-5} M_\odot$ yr$^{-1}$; e.g., Crosas & Menten 1997; Groenewegen et al. 1998), and has been extensively observed from radio to optical wavelengths, and with a variety of imaging and spectroscopic techniques. These studies have led to a fairly comprehensive model of this object, consisting of a very cool ($\gtrsim$2000 K) star surrounded by a massive, extended, roughly spherical circumstellar envelope (CSE) expanding at 14 km s$^{-1}$. High spatial resolution imaging observations show that the envelope shows organized departures from spherical symmetry on the smallest scales, which are most likely a signature that the mechanism or mechanisms that transform the round CSEs of AGB stars into planetary nebulae (PNs) with a dazzling variety of shapes with non-spherical symmetries have begun their operation in this object (Sahai 2009).

Studies of IRC+10216 over the years following its discovery have led to great progress in our understanding of the mass-loss process on the AGB, and hence the late evolution of intermediate-mass stars and their role in the enrichment of the interstellar medium (ISM) with the products of CNO and 3-$\alpha$ nucleosynthesis as well as particulate matter. But both the total amount of matter ejected into the ISM by IRC+10216’s central star and the latter’s main-sequence mass depend on the envelope’s outer extent, which remains unknown. From the deepest imaging studies undertaken so far, the CSE has been traced out to a radius of $\sim 200′$, via dust scattering of Galactic starlight (Mauron & Huggins 2000; Leão et al. 2006). This radius corresponds to material ejected from the star about 8000($D/120$) years ago.

In this Letter, we use deep Galaxy Evolution Explorer (GALEX) images to trace the IRC+10216 CSE to its outer boundary, which has become visible as a result of the CSE’s interaction with the ISM, presumably due to IRC+10216’s motion through the latter. IRC+10216 is the first carbon-rich AGB star, and the third AGB star (after R Hya and Mira, which are oxygen-rich; Ueta et al. 2006; Martin et al. 2007) in which such an interaction has now been observed. We report on our analysis of the shape, size, and structure of the CSE–ISM interaction observed in the GALEX images, provide new lower limits for the duration of heavy mass loss and the total mass of ejecta in IRC+10216, and determine its motion through the ISM.

2. OBSERVATIONS AND RESULTS

We retrieved pipeline-calibrated FUV and NUV images of IRC+10216 from the GALEX archive; the bandpass (angular resolution) is 1344–1786 Å (4.′5) and 1771–2831 Å (6.′0), respectively, and the pixel size is 1.′5 x 1.′5 (Morrissey et al. 2005). The data were taken on 2008 January 15, each with an exposure time of 8782 s. In Figure 1(a), we show a composite FUV/NUV image, and in Figure 1(b), the FUV image by itself. Field stars in each image have been removed using a customized IDL routine that replaces a small region covering each star’s point-spread function (PSF) with a tile of random noise representative of the surrounding sky. The sky noise was sampled separately at the four corners of each tile and linearly interpolated throughout, so as to preserve gradients in the local sky background to first order.

Bright nebulosity can be seen in the center of both images, around the location of IRC+10216’s central star. In addition, the FUV image shows a bright, extended (size $\sim 24′$) ring structure which is not seen in the NUV. Very faint NUV emission is, however, present in this region, as revealed via annular averages of the intensity (Section 3). The ring is seen mostly on the central star’s east side, and is surrounded on the outside by rather faint, diffuse NUV emission. On the west side, several additional diffuse patches of nebulosity can be seen, mostly in the FUV band, forming part of an elongated “tail” structure. Although the ring appears to be roughly circular around the central star’s location, closer inspection shows it to be slightly flattened in the easterly direction.

The FUV emission ring represents the interaction of the expanding CSE of IRC+10216 with the surrounding ISM, and the ring’s east–west asymmetry implies that the star is moving roughly eastward through the surrounding ISM, producing a strong shock at the eastern outer edge of its CSE. The FUV emission is most likely not due to dust scattering of the ambient interstellar radiation field (ISRF): the expected FUV-to-NUV brightness ratio in this case is $\sim 2.4$ (since the ISRF and dust scattering opacity at NUV wavelengths is, respectively, only about a factor 1.6 and 1.5 lower than in the FUV (Mezger et al.
however, a detailed model of H$_2$ excitation processes is needed to properly address this issue. This exercise is outside the scope of this Letter, and will be addressed in a follow-up paper (see Section 3; R. Sahai & C. K. Chronopoulos 2010, in preparation).

Thus the FUV ring around IRC+10216 represents the front resulting from the shocked stellar wind (i.e., the astrosheath); the outer edge of this ring corresponds to the astropause, and the inner edge to the termination shock (see Figure 2(d); Ueta 2008). The region interior to the latter consists of the unshocked, freely streaming stellar wind; the innermost part of this region is seen in both the NUV and FUV images around the central star’s location due to the scattering of ambient Galactic starlight from dust in the wind. The patchy elongated astrotail shows features which likely correspond to the vortices shed by the shock in the star’s wake, seen in the numerical simulations of a mass-losing AGB star moving through the ISM (Wareing et al. 2007). The diffuse NUV emission around the FUV ring emission most likely represents emission from interstellar material around the astropause.

3. THE ASTROPAUSE, ASTROSHEATH, AND BOW SHOCK

We have measured the astropause radius in different directions from the central star, using radial intensity cuts from the central star location at different position angles (P.A.s). Since the emission from the ring (the astrosheath) is rather faint, we have averaged the intensity over six 30° wedges spanning the eastern limb. These cuts (Figure 2) show that the radius of the shock varies across the limb, reaching a minimum radius roughly in the eastward direction, as expected from ram pressure considerations due to the (inferred) eastward motion of IRC+10216. We have fitted model radial intensities derived from a limb-brightened spherical shell to the FUV radial brightness profiles (assuming the surface brightness to be proportional to the column density) at each P.A. (measured from north, toward east), and extracted the astrosheath’s inner and outer radii ($R_1$ and $R_c$, using the nomenclature in Figure 1 of Weaver et al. 1977).

A two-piece inverse-square density profile is assumed in our model, one for $160° \lesssim r < R_1$ (where the FUV and NUV intensities are well fitted by a $r^{-\alpha}$ power law, with $\alpha$ close to unity, implying optically thin scattering of Galactic starlight by dust in a stellar wind characterized by a constant $M$ at a constant expansion velocity), and the other for $R_c > r > R_1$, with a jump in density at $r = R_1$. We cannot derive absolute values of the densities from our modeling since the proportionality factor between the brightness and the column density is purely phenomenological; furthermore, since the emission mechanisms in the two regions are different, the value of the derived density jump is not physical. The values of $R_1$ and $R_c$ which we derive are not sensitive to the assumed density profile within the astrosheath; e.g., a model with a constant density returns very similar values; however, the chi-square values of the fits in this case are somewhat poorer. The model fits provide values of $(R_1, R_c)$ in arcseconds as follows: (580, 650), (520, 600), (500, 590), (500, 600), (530, 620), and (600, 700) for the cuts at P.A. = 15°, 45°, 75°, 105°, 135°, and 165°, respectively.

We note the presence of an FUV emission “plateau” feature that can be seen for about 100° beyond the main peak at $r = R_c$, i.e., up to $r = R_2 \sim 670''$, in a radial cut of the FUV intensity averaged over a 30° wedge around P.A. = 90° (Figure 3(a)). This very faint feature can also be seen in the 30°-wide easterly

**Figure 1.** (a) Composite (NUV (red) and FUV (green)) GALEX image of IRC+10216 (the circular field of view (FOV) has a diameter of 61.6' x 61.6'); the NUV (FUV) image was boxcar smoothed using a $3 \times 3$ (2 x 2) pixels box, and displayed using a linear (square-root) stretch. The location of the central star is indicated by a *; the bright round red patches and streaks at the edges of the NUV image are due to bright stars which could not be removed, and detector edge artifacts. (b) The FUV image (same FOV as in panel (a)), which is less affected by bright star residuals and artifacts, boxcar-smoothed using a $3 \times 3$ pixels box, and displayed using a linear stretch (false color), to clearly show the detailed structure of the astropause and its tail.
cuts, i.e., at P.A. = 75° and 105° (Figure 2), and directly in the FUV image (Figure 3(b)). The presence of this sharp outer edge indicates a pile-up of gas just outside the astropause, and probably represents the bow-shock interface separating the shocked and unshocked ISM—the stellar wind material is moving supersonically in the ISM. The post-shock temperature in the bow-shock region is expected to be high, about (3/16) $\mu V_s^2 \sim 10^5$ K (assuming a strong shock, where the stellar velocity relative to the ISM, $V_s = 91$ km s$^{-1}$; Section 4), where $\mu \sim 10^{-24}$ g is the mean mass per particle for fully ionized gas. The emission in this region is most likely dominated by emission from hot gas (i.e., a combination of continuous and line emission).

The NUV radial intensity shows a sharp rise just outside the astropause, and then a drop at the bow-shock interface, but not to zero: it extends to radii well beyond the bow shock, i.e., up to ≥ 1000″, indicating that the ISM is being heated and/or excited upstream of the bow shock. We will investigate this phenomenon and possible NUV emission mechanisms (e.g., continuous emission from hot gas, line emission from the excited products of ISM ions charge exchanging with energetic neutrals from the stellar wind) in a follow-up paper (R. Sahai & C. K. Chronopoulos 2010, in preparation). Here, we merely note that an analogous situation is found for the heliosphere, where heating and compression of the local ISM (LISM) occurs upstream of the bow shock by charge exchange between secondary H atoms in the solar wind and protons from the LISM plasma (Izmodenov 2004). We also note that at the termination shock, $R_1$, the NUV intensity shows an abrupt departure (upward) from its power-law decrease seen at smaller radii (the latter results from dust scattering in the unshocked wind, see Section 4), implying that there are additional emission mechanisms operational in the astrosheath region than just H$_2$ line emission (which only contributes in the FUV band).

4. IRC+10216’s MOTION THROUGH THE ISM, MASS-LOSS DURATION, AND CIRCUMSTELLAR MASS

We estimate the star’s velocity $V_*$ through the surrounding ISM using the relationship between $l_1$, the distance of the termination shock from the star along the astropause’s symmetry axis (i.e., the termination-shock standoff distance) and $V_*$ (km s$^{-1}$) = 10 $V_{\ast,6}$ (Equation (1) of van Buren & McCray 1988):

$$l_1(\text{cm}) = 1.74 \times 10^{19} (M_{\ast, -6} V_{\ast,6} / \bar{\mu}_H n_{\text{ISM}})^{1/2} V_{\ast,6}^{-1},$$

where $M_{\ast, -6}$ is the stellar mass-loss rate in units of $10^{-6} M_\odot$ yr$^{-1}$, $V_{\ast,6}$ is the wind velocity in units of $10^3$ km s$^{-1}$, $\bar{\mu}_H$ is the dimensionless mean molecular mass per H atom, and $n_{\text{ISM}}$ is the ISM number density in cm$^{-3}$.

Given the strong asymmetry between the eastern and western hemispheres, we first make the simplifying assumption that the astropause’s symmetry axis lies in the sky plane, i.e., the inclination angle, $\phi = 90°$. We find $l_1 = R_1 = 8.6 \times 10^{17}$ cm, using the value of $R_1 = 478''$ as derived from the easterly cut (shown in Figure 3). Substituting this value of $l_1$ in Equation (1), with $M_{\ast, -6} = 20$, $V_{\ast,6} = 0.014$, $\bar{\mu}_H = 1.33$ (for an 89/11 mixture of hydrogen/helium), and $n_{\text{ISM}} = 1$, we get $V_*= 91$ km s$^{-1}$. Note that the value of $V_*$ (1) does not depend on the poorly known distance, $D$, to IRC+10216, since both $l_1$ and $M_{\ast, -6}$ scale linearly with $D$ and (2) depends only weakly on the uncertain value of the ISM density at IRC+10216’s location.

In order to estimate the inclination angle accurately, we will need to fit a three-dimensional model of a paraboloidal-shaped emitting astrosheath to the observed emission, which is outside the scope of this Letter. Mac Low et al.’s (1991: MLetal91) paraboloidal bow-shock models for various inclination angles (their Figure 5) show that as $\phi$ becomes smaller, the ratio of the radial distance between the star and the apex of the projected emission paraboloid, to the (unprojected) standoff distance, becomes larger. A visual comparison of IRC+10216’s FUV emission morphology (Figure 1) with the surface brightness contours in Figure 5 of MLetal91 indicates that $\phi$ could be small, ~30°, in which case our measured value of $R_1$ is larger than $l_1$ by a significant factor. We speculate that this factor may be as large as ~1.5−2, by comparing the length of the (unprojected) standoff distance vector, to the distance between the star and the apex as defined by the emission contours for $\phi = 30°$ and 90° in Figure 5 of MLetal91. Thus the value of $V_*$ may be as high as ~160 km s$^{-1}$.

The FUV emission traces the spherical AGB stellar wind to a much larger distance from the star than previous measurements (200°; Leão et al. 2006). For example, the radial extent of
the astropause along directions orthogonal to the direction of motion of the central star, i.e., at positions angles, P.A. = 0° and 180°, is 700" (84,000 AU at D = 120 pc). Hence, we can use the astropause size to substantially revise (upward) previous estimates of the duration, P, of heavy mass loss in IRC+10216 (8000 years; Leão et al. 2006). We estimate P by deriving expansion timescales (Pu, Ps) for the unshocked and shocked wind regions separately; Pu = 19,480 years from the ratio of the termination shock radius (478") to Vw, and Ps = 49,740 years from the ratio of the astrosheath width (102") along the symmetry axis (since the velocity vectors are radial along this axis) to an average velocity for this region, \( V_s = 1.17 \text{ km s}^{-1} \). We take \( V_s = V_s/2 \), where \( V_s = V_w(\gamma - 1)/(\gamma + 1) = V_w/6 = 2.33 \text{ km s}^{-1} \) is the velocity in the astrosheath just beyond the termination shock, with \( \gamma = 7/5 \) for diatomic gas, and assuming the latter to be adiabatic. The actual value of \( V_s \) should be less than the adiabatic value, since the astrosheath appears to have cooled to some degree (the astrosheath’s average width of 100", or \( 1.8 \times 10^{17} \text{ cm} \), is smaller than the adiabatic value, \( \approx 0.4711 = 4 \times 10^{17} \) (Equation 2); Van Buren & McCray 1988). Furthermore, once a complete balance has been established between the ram pressures of the stellar wind and the ISM, the leading edge of the astropause remains a fixed distance ahead of the moving star (Weaver et al. 1977). Hence, \( P = P_u + P_s = 69 \), 220 years is a lower limit, and we conclude that IRC+10216 has been undergoing mass loss for at least 69,000 years, and the total CSE mass is \( > 1.4 M_\odot \).

In summary, the GALEX images of IRC+10216 show an unprecedented detailed picture of the interaction of the wind from an AGB star with the ISM, due to its motion in the latter, allowing us to identify all the important structural features expected from theoretical models of such interactions. This interaction process has been observed in the past for other AGB stars (e.g., R Hya: Ueta et al. 2006, Mira: Martin et al. 2007). It is noteworthy that the shock structure on the east side of IRC+10216 is relatively smooth and well defined, and does not show the large-scale instabilities (of the order of the standoff distance) which Blondin & Koerwer (1998) predict for stars with slow, dense winds moving relative to the ISM at high speeds (of order 60 km s\(^{-1}\)). Our study provides valuable new data for understanding the CSE–ISM interaction, especially since the mass-loss rate in IRC+10216 is about 2 orders of magnitude greater than in R Hya and Mira. New hydrodynamic simulations of stellar-wind–ISM interactions (such as, e.g., by Wareing et al. 2007) to explore the high mass-loss regime represented by IRC+10216’s stellar wind should be carried out.

**Note added in proof:** After this paper was accepted, we were informed of an AAS meeting abstract on GALEX observations of IRC10216’s atmosphere by M. Seibert, D. C. Martin, & J. D. Neill (2010, BAAS, 41, 296).

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