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IDENTIFICATION OF GALACTIC WIND CANDIDATES USING EXCITATION MAPS: TUNABLE-FILTER DISCOVERY OF A SHOCK-EXCITED WIND IN THE GALAXY NGC 1482

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ABSTRACT

Multiline imaging of the nearby disk galaxy NGC 1482 with the Taurus Tunable Filter on the Anglo-Australian Telescope reveals a remarkable hourglass-shaped [N II] λ6583/Hα excitation structure, suggestive of a galactic wind extending at least 1.5 kpc above and below the disk of the host galaxy. Long-slit spectroscopy confirms the existence of a large-scale outflow in this galaxy. The entrained wind material has [N II] λ6583/Hα ratios in excess of unity, while the disk material is characterized by H II region–like line ratios indicative of a starburst. Expansion velocities on the order of 250 km s^{-1} are detected in the wind material, and a lower limit of 2×10^{53} ergs is derived for the kinetic energy of the outflow based on the gas kinematics and the amount of ionized material entrained in the outflow. This is the first time to our knowledge that a galactic wind has been discovered using excitation maps. This line ratio technique represents a promising new way to identify wind galaxy candidates before undergoing more time-consuming spectroscopic follow-ups. This method of selection may be particularly useful for samples of galaxies at moderate redshifts.

Subject headings: galaxies: active — galaxies: individual (NGC 1482) — galaxies: kinematics and dynamics — galaxies: starburst — galaxies: statistics

1. INTRODUCTION

In an effort to better constrain the morphology, kinematics, and origin of the warm ionized gas on the outskirts of galaxies, we have obtained deep emission-line images of several nearby starburst and active galaxies using the Taurus Tunable Filter (TTF) on the 3.9 m Anglo-Australian and 4.2 m William Herschel Telescopes (see Veilleux 2001 for more detail). In the course of this study, we discovered a remarkable emission-line structure in the early-type spiral galaxy NGC 1482. This galaxy has so far received relatively little attention in the literature. It is classified as a peculiar SA0/a in the Revised Third Catalog (de Vaucouleurs et al. 1991) based primarily on the presence of a dust lane across the disk of the galaxy. Located at a distance of 19.6 Mpc (Tully 1988), it is an infrared-bright galaxy with $\log [L_{\rm IR}/L_{\odot}] = 10.5$ (e.g., Soifer et al. 1989; Sanders, Scoville, & Soifer 1991) that is rich in molecular gas and dust (e.g., Sanders et al. 1991; Young et al. 1995; Chini, Kruegel, & Lemke 1996) and is undergoing vigorous star formation (e.g., Moshir et al. 1990; Devereux & Hameed 1997; Thornley et al. 2000). In a recent emission-line imaging survey of early-type spirals, Hameed & Devereux (1999) noticed the presence in NGC 1482 of “filaments and/or chimneys of ionized gas extending perpendicular to the disk.” The present study expands on the results of Hameed & Devereux, using deeper emission-line maps at Hα and [N II] λ6583 and complementary long-slit spectra. We find that the [N II]/Hα excitation map of this galaxy is particularly useful at distinguishing between the star-forming disk and the entrained, shock-excited wind material. This excitation signature could be used in the future to more efficiently identify powerful galactic winds in the local and distant universe.

2. OBSERVATIONS

NGC 1482 was observed on the night of 2000 December 16 using the “blue” TTF (Bland-Hawthorn & Jones 1998) at the Anglo-Australian Telescope. This instrument was used in the “charge shuffling/band switching” mode to maximize sensitivity to faint flux levels. The basic idea is to move charge up and down within the detector at the same time as switching between two discrete wavelengths with the tunable filter. In this way, the on-band image is obtained nearly simultaneously as the off-band (continuum) image. For our observations, the charges were moved every minute, and the chip was read out after a total integration time of 32 minutes (i.e., 16 minutes on-band and 16 minutes off-band). Four sets of observations were obtained of NGC 1482: two centered on redshifted Hα for a total on-band integration time of 32 minutes and two centered on redshifted [N II] λ6583 for the same duration. The continuum images for each set of observations were obtained in a straddle mode, where the off-band image is made up of a pair of images that “straddle” the on-band image in wavelength; this greatly improves the accuracy of the continuum removal since it corrects for slopes in the continuum and underlying absorption features (see also Maloney & Bland-Hawthorn 2001). The wavelength calibration was checked before and after each pair of observations and was found to be stable. The bandpass of the TTF was set to 14.6 Å throughout the observations. This bandpass was chosen to separate Hα λ6563 emission from [N II] λλ6548, 6583 emission, while still producing a monochromatic field of view of several arcminutes, much larger than the total extent of NGC 1482. Phase effects due to the angular Fabry-Perot interferometer response can therefore be safely ignored in the rest of the discussion. The MITLL2A CCD was used for these observations, providing a pixel scale of 0″.37 pixel^{-1} and a field of view of $10' \times 10'$. The observations were obtained under photometric and ~1″.5 seeing conditions.

On 2001 September 19–21, several complementary long-slit spectra were obtained of NGC 1482. The Dual-Beam Spectrograph on the MSSSO 2.3 m telescope was used at the Nasmyth f/17.9 focus with the 1200B and 1200R gratings. The CCD was a SITe 1752 × 532 × 15 μm pixel device. At a plate scale of 0″.91 pixel^{-1}, a 2″ slit gave a resolution of 1.2 Å FWHM and a wavelength coverage of 4400–5400 Å and 6100–7050 Å. On one occasion, the slit was aligned along the minor axis of the

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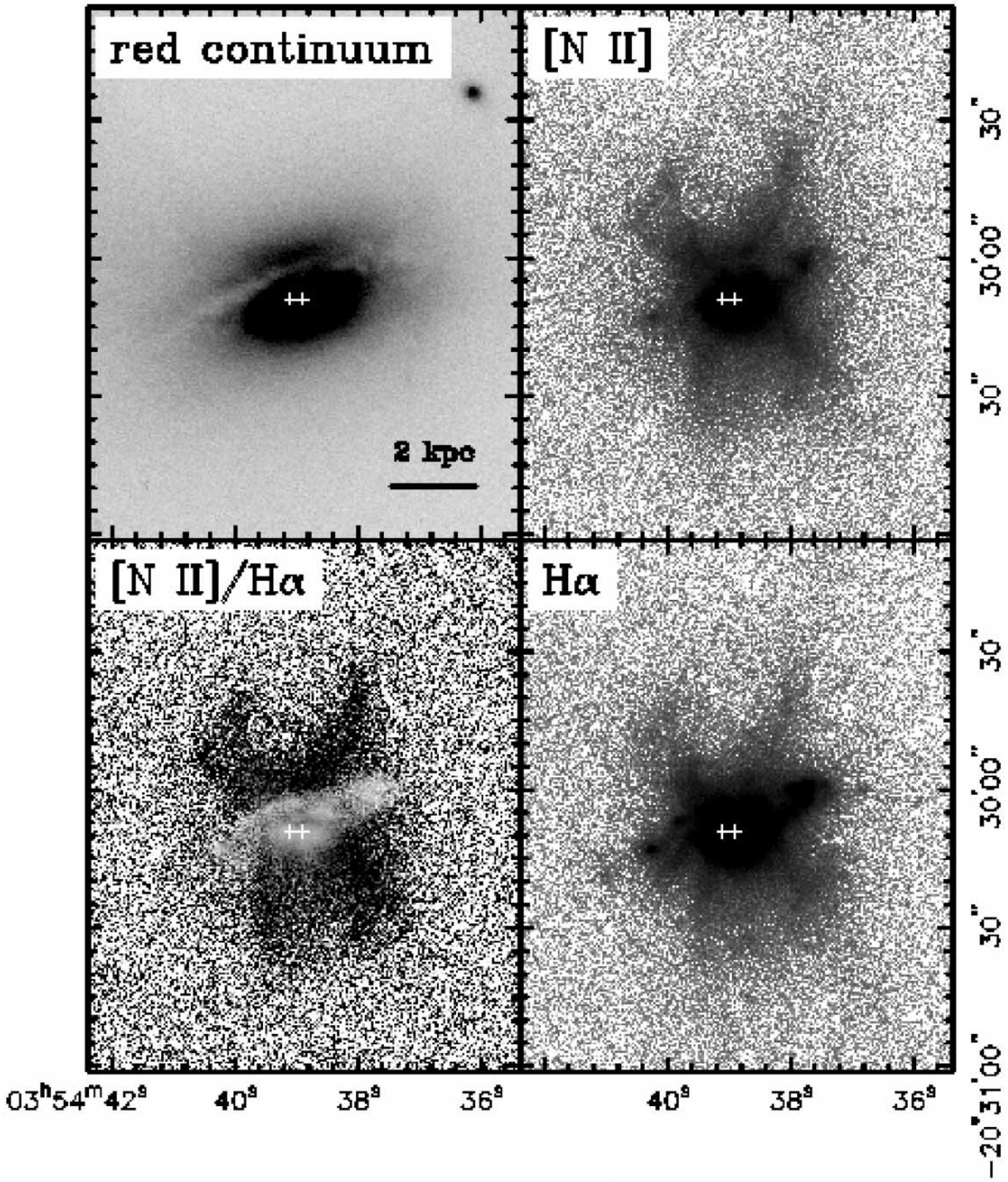

FIG. 1.—Narrowband images of NGC 1482 obtained with the TTF. *Clockwise from upper left*: Red continuum, [N II] λ6583 line emission, Hα line emission, and [N II] λ6583/Hα ratio. Right panels are on a logarithmic intensity scale, while left panels are on a linear scale. North is at the top, and east is to the left. The positions of the continuum peaks are indicated in each image by two crosses. The spatial scale, indicated by a horizontal bar at the bottom of the red continuum image, is the same for each image and corresponds to ~21″, or 2 kpc for the adopted distance of 19.6 Mpc for NGC 1482. The [N II] λ6583/Hα ratio is below unity in the galaxy disk, but larger than unity in the hourglass-shaped nebula above and below the disk. This structure is highly suggestive of a galactic wind.

galaxy (P.A. ≈ 13°; de Vaucouleurs et al. 1991) passing through the nucleus. In all other cases, the slit was positioned along 103° and offset from 0″ to ±16″ from the major axis of the galaxy. The exposure times were typically 1200 s.

3. RESULTS

Figure 1 shows the distribution of the Hα and [N II] λ6583 emission in NGC 1482. Strong Hα and [N II] emission is detected along the plane of the host galaxy (P.A. ≈ 103°). In addition, an hourglass-shaped structure is seen in both Hα and [N II] λ6583, extending along the minor axis of the galaxy at least ~1.5 kpc above and below the galactic plane. This structure is more easily visible in [N II] λ6583 than in Hα. This is particularly apparent in the lower left panel of Figure 1, where we present an [N II]/Hα ratio map of this object. The [N II] λ6583/Hα ratios measured in the disk of the galaxy (≈0.3 [outer disk] to 0.6 [inner disk]) are typical of photoionization by stars in H II regions, but the ratios in the hourglass structure are 3–7 times larger ([N II] λ6583/Hα ≈ 1.0–2.3). This ratio of a collisionally excited line to a recombination line is fundamentally a measure of the relative importance of heating and ionization (e.g., Osterbrock 1989).

[N II]/Hα ratios enhanced relative to H II regions are often observed in the extraplanar material of normal disk galaxies, including our own (e.g., Rand, Kulkarni, & Hester 1990; Veilleux, Bland-Hawthorn, & Cecil 1995a; Reynolds, Haffner, &

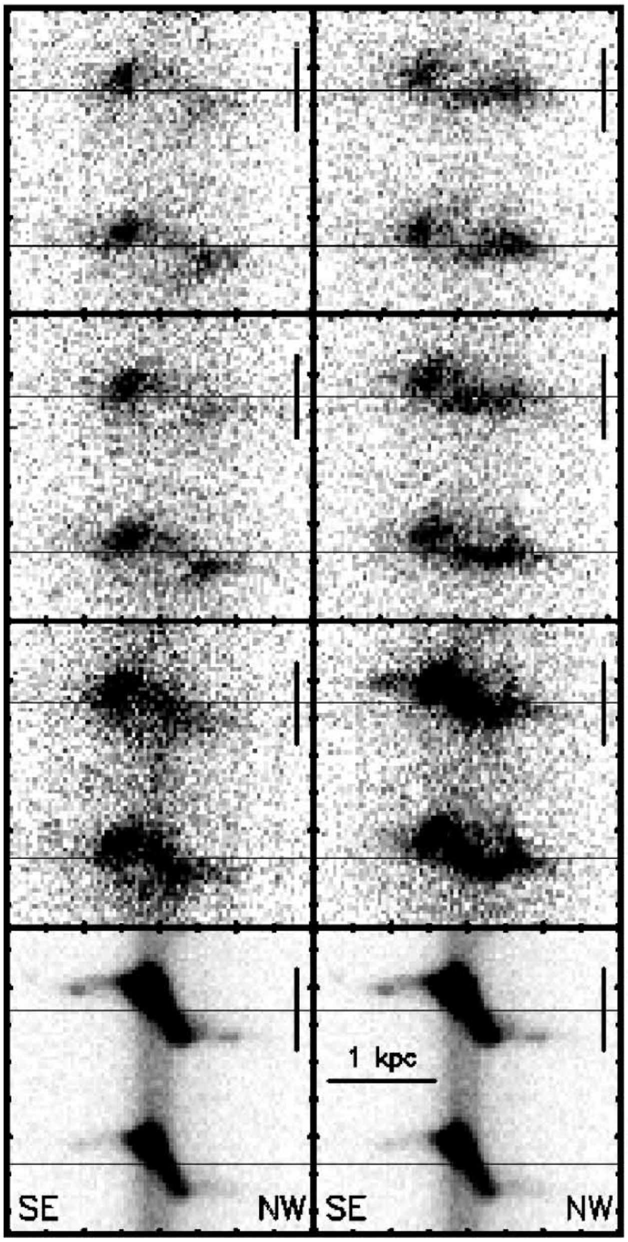

FIG. 2.—Sky-subtracted long-slit spectra obtained parallel to the galactic disk (P.A. ~ 103°). For each panel, southeast is to the left, and northwest is to the right. From bottom to top, the spectra displayed on the left are offset to the northeast by 0″, 9″–10″, 11″–12″, and 13″–14″ from the major axis of the host galaxy. Spectra displayed on the right are offset by approximately the same quantities in the southwest direction. The vertical segment in each panel represents 500 km s^{-1}. The presence of line splitting above and below the disk confirms the presence of a large-scale wind in this galaxy.

Tufte 1999; Hoopes, Walterbos, & Rand 1999; Rossa & Dettmar 2000; Collins & Rand 2001; Miller 2002). Although photoionization by the hardened and diluted radiation field from OB stars in the disk is partially responsible for these peculiar line ratios (e.g., Sokolowski 1992; Bland-Hawthorn, Freeman, & Quinn 1997), a secondary source of ionization or heating is often needed to explain in detail the runs of line ratios in these galaxies (e.g., Reynolds et al. 1999; Collins & Rand 2001; Miller 2002). The extreme [N II] λ6583/Hα ratios in the hourglass structure of NGC 1482 also require an additional source of heating. Ruling out photoionization by an active galactic nucleus (AGN) based on the lack of evidence for genuine nuclear activity in NGC 1482 (e.g., Kewley et al. 2000), the most likely explanation for these unusual line ratios is shock ionization. Interaction of an energetic large-scale outflow with the ambient material of a gas-rich host galaxy will cause shock waves with velocities of 100–500 km s^{-1}. The shocks will produce a strong flux of extreme-ultraviolet and soft X-ray radiation that may be absorbed in the shock precursor H II region (e.g., Dopita & Sutherland 1995). Arguably one of the best examples known of shock-excited nebulae associated with large-scale galactic winds is the kiloparsec scale superbubble in the galaxy NGC 3079 (e.g., Filippenko & Sargent 1992; Veilleux et al. 1994; Cecil et al. 2001). Large [N II] λ6583/Hα ratios are observed throughout the bubble, reaching values of about 3 at the base of the bubble where the widths of the emission lines exceeds 400 km s^{-1}. H II region–like line ratios are observed everywhere else in the disk (Veilleux et al. 1995a).

The kinematics of the line-emitting gas derived from our long-slit spectroscopy of NGC 1482 confirm that the hourglass structure is due to a large-scale galactic wind and that the extreme line ratios are produced through shocks. Figure 2 shows the disturbed kinematics in the extraplanar material. Line splitting of up to ~250 km s^{-1} is detected along the axis of the hourglass structure out to at least 16″ (1.5 kpc) above and below the galaxy disk. Normal galactic rotation dominates the kinematics of the gas within 5″–6″ (~500 pc) from the disk. Maximum line splitting often coincides with regions of low emission-line surface brightness. These results can be explained if the extraplanar emission-line material forms a biconical edge-brightened structure that is undergoing outward motion away from the central disk. In this case, the blueshifted (redshifted) emission-line component corresponds to the front (back) surface of the bicone. The lack of obvious velocity gradient in the centroid of the line emission suggests that the main axis of the bicone lies close to the plane of the sky. The fact that the amplitude of the line splitting does not decrease significantly with distance from the galaxy indicates that the entrained material is not experiencing significant deceleration (i.e., it is a blown-out wind).

The mass involved in this wind can be estimated from the total Hα emission outside of the disk. Defining the wind material as having [N II] λ6583/Hα ≥ 1, we get a wind Hα flux (luminosity) of ~1.7×10^{-13} ergs s^{-1} cm^{-2} (~8.0×10^{39} ergs s^{-1}) with an uncertainty of about ±25% to 30%. The [S II] λλ6731/6716 line ratios measured from our long-slit spectra indicate that the entrained material has a density of $n_e \lesssim 100$ cm^{-3}. The mass in entrained line-emitting material is therefore $\gtrsim 3.6 \times 10^5\ n_{e,2}^{-1}\ M_\odot$, where $n_{e,2}$ is normalized to 100 cm^{-3} (assuming case B recombination and an effective recombination coefficient for Hα of 8.6×10^{-14} cm^{-3} s^{-1}; Osterbrock 1989). A correction for possible dust extinction intrinsic to NGC 1482 will further increase this number [note that the extinction due to our Galaxy, $E(B-V) = 0.04$, is negligible; Schlegel, Finkbeiner, & Davis 1998]. A simple kinematic model can be used to estimate a few key wind parameters. The bisymmetric morphology and kinematics of the wind nebula in NGC 1482 suggest that the entrained material lies on the surface of a cylindrically symmetric bicone. If most of the gas motion is tangential to the surface of the bicone, and given that the axis of the bicone lies approximately in the plane of the sky, the radial outflow velocity is $V_{\rm out} = \Delta V/(2 \sin\theta)$, where ΔV is the observed maximum line splitting and θ is the angle between the surface and the main axis of the bicone. Taking $\Delta V \approx 250$ km s^{-1} and $\theta \approx 30°$ based on the morphology of the wind (Fig. 1), we get $V_{\rm out} \approx 250$ km s^{-1}. Given that ΔV and θ are observed to be approximately constant throughout the wind nebula, the total kinetic energy involved in the outflow is $\gtrsim 2 \times 10^{53}\ n_{e,2}^{-1}$ ergs.

The dynamical timescale of the outflow can be estimated from the outflow velocity and radial extent: $\tau_{\rm dyn} \approx R/V_{\rm out} \approx 6 \times 10^6$ yr. Combining the dynamical timescale and kinetic energy of the outflow, we derive a time-averaged kinetic energy injection rate of $\gtrsim 1 \times 10^{39}\, n_{e,2}^{-1}$ ergs s^{-1}. This can be compared with the energy injection rate from star formation in NGC 1482 of $\sim 7 \times 10^{42}\, f_{\rm out} L_{\rm IR,\,11} \approx 2 \times 10^{42}\, f_{\rm out}$ ergs s^{-1}, where $L_{\rm IR,\,11}$ is the infrared luminosity in units of $10^{11}\, L_\odot$ and $f_{\rm out}$ is the fraction of the star-forming disk that is contributing to the outflow (Veilleux et al. 1994, eq. [12]). The broad base of the wind nebula near the galaxy disk (Fig. 1) suggests that the source of energy for the wind is distributed over a region of about 2 kpc, i.e., $f_{\rm out} \approx 50\%$ of the total extent of the star-forming (Hα-emitting) portion of the disk. The starburst at the base of the wind nebula in NGC 1482 is therefore powerful enough to drive the outflow as long as $n_e \gtrsim 0.1$ cm^{-3}.

4. THE USE OF EXCITATION MAPS TO IDENTIFY STARBURST-DRIVEN WIND GALAXIES

The traditional method of identifying galaxy-scale winds in starburst galaxies is to look for the kinematic signature (e.g., line splitting) of the wind along the minor axis of the host galaxy disk. Edge-on disk orientation reduces contamination of the wind emission by the underlying disk material and facilitates the identification. This method is time-consuming since it requires deep spectroscopy of each candidate wind galaxy with a spectral resolution of $\lesssim 100$ km s^{-1}. Line ratio maps like the one shown in Figure 1 represent a promising new way to detect galactic winds in starburst galaxies. The line ratio method requires taking only narrowband images of candidate wind galaxies centered on two (or more) key diagnostic emission lines that emphasize the contrast in the excitation properties between the shocked wind material and the star-forming disk of the host galaxy. [N II] λ6583/Hα, [S II] λλ6716, 6731/Hα, and [O I] λ6300/Hα are the optical line ratios of choice for $z \lesssim 0.5$ galaxies (these ratios are enhanced in the wind of NGC 1482), while [O II] λ3727/Hβ and [O II] λ3727/[O III] λ5007 could be used for objects at larger redshifts. The spatial resolution of these images must be sufficient to distinguish the galaxy disk from the wind material. Using NGC 1482 as a template, we find that high–[N II]/Hα winds in edge-on starburst galaxies would still be easily detected out to a distance of ~200 Mpc under 1″ resolution. Imagers equipped with adaptive optics systems should be able to extend the range of these searches by an order of magnitude.

This method relies on the dominance of shock excitation in the optical line-emitting wind component. Surveys of local powerful wind galaxies (e.g., Heckman, Armus, & Miley 1990; Bland-Hawthorn 1995; Veilleux et al. 1995b; Lehnert & Heckman 1996; Veilleux 2001) confirm that shocks are generally the dominant source of excitation in the wind material. These shock-dominated wind nebulae present line ratios that are markedly different from the star-forming disks of the host galaxies. The case of the superbubble in NGC 3079 has already been discussed in § 3. At the other end of the excitation spectrum is the wind in M82. The [N II]/Hα map of the southern wind lobe of M82 (Fig. 4 of Shopbell & Bland-Hawthorn 1998) presents two distinct fanlike structures with H II region–like ratios originating from the two bright star-forming regions in the disk of this galaxy. The line ratio technique would not be able to distinguish between line emission from this type of photoionization-dominated wind nebulae and contamination from a star-forming disk seen nearly face-on. Blind searches for galactic winds based on the excitation contrast between the disk and wind components would therefore favor the detection of winds in edge-on hosts where the wind component is not projected onto the disk component. This orientation bias would need to be taken into account to get a complete census of starburst-driven wind galaxies. AGN-driven winds may also contaminate samples selected from excitation maps if the spatial resolution is not sufficient to separate the active nucleus from the disk material.

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