A NEAR-INFRARED SURVEY OF THE INNER GALACTIC PLANE FOR WOLF–RAYET STARS. I. METHODS AND FIRST RESULTS: 41 NEW WR STARS

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ABSTRACT

The discovery of new Wolf–Rayet (WR) stars in our Galaxy via large-scale narrowband optical surveys has been severely limited by dust extinction. Recent improvements in infrared technology have made narrowband–broadband imaging surveys viable again. We report a new J, K, and narrowband imaging survey of 300 deg2 of the plane of the Galaxy, spanning 150 degrees in Galactic longitude and reaching 1 degree above and below the Galactic plane. The survey has a useful limiting magnitude of K = 15 over most of the observed Galactic plane, and K = 14 within a few degrees of the Galactic center. Thousands of emission line candidates have been detected. In spectrographic follow-ups of 173 WR star candidates we have discovered 41 new WR stars, 15 of type WN and 26 of type WC. Star subtype assignments have been confirmed with K-band spectra, and distances approximated using the method of spectroscopic parallax. A few of the new WR stars are among the most distant known in our Galaxy. The distribution of these new WR stars is seen to follow that of previously known WR stars along the spiral arms of the Galaxy. Tentative radial velocities were also measured for most of the new WR stars.

Key words: Galaxy: disk – Galaxy: stellar content – stars: emission-line, Be – stars: Wolf–Rayet – surveys

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1. INTRODUCTION

1.1. Motivation

It is extraordinary but true that the galaxy of the Local Group whose global stellar populations are least well observed is our own Milky Way. Deeply immersed within the optically opaque, dusty lanes of our Galaxy’s spiral arms, astronomers have been frustrated for centuries in their attempts to map the stellar populations of the Milky Way. A complete census of our Galaxy for every member of even one class of star would have seemed like an impossible goal even a decade ago. Major advances in instrumentation are transforming this daunting task from near-impossibility to increasingly likely. Wide-field, high-resolution, sensitive surveys, particularly in the near-infrared and X-ray parts of the electromagnetic spectrum (where the Galaxy is relatively transparent), are key to locating and characterizing all members of one or more classes of stellar object. The goal of the project described in this paper is to detect and spectrographically characterize at least 90% of the Wolf–Rayet (WR) stars in the Milky Way within 10 years.

A set of well defined tests of stellar evolution theory will follow from detections of complete samples of WR and other related stars. For example, the radial abundance gradient across our Galaxy and the increase of the WR/O number-ratio with increasing Z suggests that many more WR stars will be found in the inner parts of the Milky Way than in the outer regions. In addition, our previous Hubble Space Telescope (HST) survey of the H II regions in the ScIII galaxy NGC 2403 (Drissen et al. 1999) suggested that the distribution of WR and red supergiant stars (RSG) is a sensitive diagnostic of the recent star-forming history of these large complexes; young cores of O and WR stars are surrounded by older halos containing RSG. Theory predicts that the number-ratio WR/O increases with increasing metallicity; thus, relatively fewer WR stars form at lower Z. We will also be able to determine if superclusters, dominated by WR stars, are common in the Milky Way. Finally, we note that WR stars are predicted to end their lives as supernovae, and in rare cases as gamma-ray bursts. The WR stars in the Milky Way may be abundant enough for one to erupt as a Type Ib or Ic supernova within a few generations. This comes from the assumption that the MW contains ~6000 WR stars, each lasting ~5 × 105 yr. The clear identification of a WR star as the progenitor of one of these eruptions would be a dramatic confirmation of a key prediction of stellar evolution theory.

1.2. Wolf–Rayet Stars

WR stars are massive (with initial masses greater than ~20 M⊙ at Z⊙) stars with strong winds (M ~ 10−7 M⊙ yr−1) displaying the heavier elements created by what are normally internal nuclear processes. Distinctive spectra with strong, broad emission lines of helium, and either nitrogen (WN) or carbon (WC) are the defining observational characteristics of WR stars. As they have relatively short lifetimes (about 5 × 105 yr), WR stars are excellent tracers of star formation, and they are also believed to be Type Ib or Ic supernova progenitors, because they have removed their outer H-rich layers (WN) or even He-rich layers (WC/O).

About 300 WR stars have been previously identified in the Milky Way (van der Hucht 2006), with distribution models predicting ~1000–6500 total expected (Shara et al. 1999;
van der Hucht 2001). Optical narrowband surveys have been severely limited by interstellar extinction (Shara et al. 1999), and so the natural solution is to turn to the near infrared. Emission line magnitudes of 40 known WR stars are presented in Appendix A. A model of the Milky Way, predicting the numbers and distributions of WR stars visible in the K band is presented in Appendix B.

In an initial attempt at a narrowband near-infrared survey Homeier et al. (2003) had limited success, while Hadfield et al. (2007) were somewhat more successful with their color-based selection of objects from the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) and GLIMPSE (Benjamin et al. 2003) surveys.

Utilizing a new narrowband survey, described in Section 2 along with the candidate selection methods, we have found 41 new WR stars: 15 WN and 26 WC. Spectrographic follow-up and data reduction are described in Section 3. Our resulting K-band spectra, line measurements, and subtype classification are presented in Section 4. Distances to the new WR stars are calculated and their distribution within the Galaxy considered in Section 5. Our conclusions are summarized in Section 6.

2. OBSERVATIONS

The most reliable optical technique to detect individual WR stars in crowded fields consists of subtracting a normalized continuum image from an image obtained with a narrowband filter centered on the He II 4686 Å line. This works well for individual WR stars with equivalent widths of He II (4686) 10–15 Å or larger, and even for dense, unresolved clusters that include a very small fraction of WR stars (Drissen et al. 1993). Unfortunately, dust extinction makes this technique infeasible for the large majority of Galactic WR stars. Only in the near-infrared can we hope to detect the WR stars farther than about 5 kpc.

A near-infrared survey of the plane of the Galaxy was carried out under the umbrella of the SMARTS consortium (see http://www.astro.yale.edu/smarts/). The imaging data were taken over approximately 200 nights in 2005–2006 on the Cerro Tololo Inter-American Observatory (CTIO) 1.5 m telescope, using the Université de Montréal’s CPAPIR camera. Images are 35’’ on a side, with a plate scale of 1.03 per pixel, and cover 1° above and below the Galactic plane from Galactic longitude $l = -90°$ to $l = 60°$. Each of the 1200 fields was imaged in the J and K bands, and through a selection of narrowband filters designed for identifying WR stars.

Motivated by the WR infrared spectra in Figer et al. (1997), we purchased a filter set (Table 1) which targeted the emission line features He I 2.062 μm, C IV 2.081 μm, H I Brγ 2.169 μm, and He II 2.192 μm. In addition, two narrowband continuum filters were used which were selected to be relatively devoid of emission lines, one blueward (2.033 μm) and one redward (2.255 μm) of the emission line filters. These were then used to linearly interpolate a continuum magnitude at each of the emission line bands, so we could calculate the difference in measured and interpolated magnitudes, $\Delta m$, indicative of emission or absorption in that band. In this paper, we are working from a catalog of the calculated $\Delta m$ values for all of the stars contained in the survey area which had been processed by the time of our spectroscopic follow-up. This consisted of about 75% of the survey area, and in general we excluded those areas most crowded with stars, in particular the approximately 8 degrees in longitude closest to the Galactic center.

### Table 1

| Filter Name | $\lambda$ (μm) | $\Delta l$ (μm) | Exp-time (s) |
|-------------|----------------|----------------|-------------|
| CONT1       | 2.033          | 0.020          | 29.70       |
| He I        | 2.062          | 0.010          | 59.40       |
| C IV        | 2.081          | 0.020          | 29.70       |
| Brγ         | 2.169          | 0.020          | 29.70       |
| He II       | 2.192          | 0.020          | 29.70       |
| CONT2       | 2.255          | 0.100          | 10.80       |

2.1. Image Processing

The more than 77,000 science and dome flat images of the survey require a customized, streamlined pipeline to reduce this large amount of data. The pipeline was constructed (by JG and DZ) in IDL and uses the 2MASS catalog extensively as a reference for both astrometry and photometry. Each of the ~ 1200 fields has been imaged in each of the eight filters at seven dither positions with separations of ~ 15”. Dome flats were used to flatten each of the images for sensitivity and chip defects. These seven dither positions were median combined together without shifting to remove most of the stellar sources and to create a sky image. The sky image was subtracted from each image.

Sources for each field/filter were matched to 2MASS to determine the world coordinate system (WCS). Once a WCS was fit, another iterative process was performed to minimize the residuals to 2MASS and determine the best geometric distortion solution. The IDL procedure WARP_TRI applied the geometric distortion solution. The IDL procedure HASTOM aligned all the images taken in a dither series. These images were combined to create a final deep exposure.

2.2. Photometry

Sources were identified as WR candidates through emission in the narrowband filters. This made it necessary to have not only the magnitude of a source in the narrowband filter, but also the magnitude of the continuum at that wavelength. As a result, each narrowband filter had to be examined concurrently with the CONT1 and CONT2 filters.

Sources on the final deep exposures were detected using the IDL procedure FIND. Aperture photometry was then carried out using the IDL procedure APER with a 2 pixel aperture and a sky annulus from 10 to 20 pixels. Objects matched to the 2MASS catalog (at least 100 in each field) were used to determine a zero point for each filter in each deep image. An object with a flat spectrum through our filters has the same magnitude in all six filters.

Sources were considered matched across filters if their positions were consistent within 0.5 pixel. These matched sources with 2MASS-calibrated magnitudes were then used to construct emission–magnitude diagrams (EMDs). An EMD was constructed for each narrowband filter with the wavelength-interpolated continuum magnitude versus continuum-subtracted narrowband magnitude. The stars scatter around a continuum-subtracted narrowband magnitude of zero. In each magnitude bin we calculate the standard deviation sigma of the continuum-subtracted narrowband magnitude. Objects that are 5σ or more in the negative direction from the locus of stars are considered candidates. We determined the offset to convert instrumental magnitudes to apparent magnitudes using the 2MASS $K_s$ band.
catalog. The images were divided into an 8 × 8 grid, with each of the 64 areas having an individually determined offset, to compensate for an observed color dependence (probably due to variable reddening) across the field. The IDL procedure APER determined the magnitude for the source at the coordinates given by 2MASS.

Once the offsets to convert to apparent magnitude were calculated, FIND, an IDL procedure, identified sources in an image that were a given deviation above the background. APER found the instrumental magnitude for the sources, which were then converted to apparent magnitudes. The CONT1 filter was taken as a reference image and HASTROM aligned all filters from a field. The sources from CONT1 were then matched to the sources from the CONT2 image and sources within 0.5 pixels were kept as matches. The matched sources were then compared to the sources of a narrowband filter. The result was a list of sources found within 0.5 pixels of each other in both of the continuum filters and the narrowband filter. A linear fit was found between the CONT1 and CONT2 filter magnitudes of each source. Then, using the central wavelength for the narrowband filter, an interpolated continuum value at the narrowband wavelength was determined. The magnitude of the source in the narrowband filter was then subtracted from the interpolated continuum value, giving the negative emission magnitude for the source in that narrowband filter. The emission magnitude for a source was also estimated by subtracting the CONT1 and the CONT2 magnitude from the narrowband magnitude, resulting in a total of three estimates for the emission magnitude of a source. An EMD of continuum magnitude versus emission magnitude was created for each source. An EMD of emission magnitude of a source. An EMD of emission magnitude for a source was also estimated by subtracting the CONT1 and the CONT2 magnitude from the narrowband magnitude, resulting in a total of three estimates for the emission magnitude of a source. An EMD of continuum magnitude versus emission magnitude was created for each narrowband filter and the standard deviation was determined for the sources in bins of 1 mag. Sources that had emission magnitudes of 5σ or greater from the center of the EMD were marked as WR candidates. A star was then blinked by eye to remove any candidates that did not resemble stars.

2.3. Candidate Selection

In this initial, exploratory phase of the survey we used two techniques when selecting targets for spectroscopic follow-up. We began by selecting targets with such powerful emission lines that the star appeared brighter in the narrowband images when compared to the continuum images even when examined by eye. This corresponds to a minimum of 0.5 to 1 mag difference in brightness between the narrow- and broadband images. We initially selected candidates displaying a brightening of at least 0.5 mag in at least one narrowband image relative to the continuum. This resulted in the detection of 34 new planetary nebulae (which will be reported elsewhere) whose very strong, sharp emission lines, He i 2.058 μm and Brγ 2.166 μm, fell within our He i and Brγ narrowband imaged fields. A few of the planetary nebulae were slightly resolved on the Brγ narrowband images. No new WR stars have yet been found this way.

Our second, much more successful, technique relied on using known WR stars to calibrate our selection of targets. Forty known WR stars were selected within the survey area, and patterns were found in their narrowband Δm values which distinguished broad subtypes of WR stars (see Appendix A). WC stars generally showed strong (−0.8 mag or less) excess emission in the C IV filter, and slightly weaker emission (between −0.4 and −0.8 mag) in the He i filter, due to the blue side of the C IV line extending into the range of the He i narrowband filter. Early WN stars generally showed moderate emission in the Brγ filter and the He i filter, but slight absorption (0.1 mag) in both He i and C IV.

Using these criteria, 173 candidate targets were selected which appeared at least 5σ brighter in their narrowband filter than did other stars in the field and which also fit the criteria suggested by the known WRs. Though we are reliably detecting stars to magnitude 14–14.5 in all of the filters (by judicious choice of exposure times), during this exploratory stage candidates were selected to have emission-band magnitudes brighter than K = 11.5. This is because the initial spectroscopic follow-up is being done with a 1.5 m telescope (see below). (Thousand of uncrowded 5σ candidates as faint as K = 14.5 will be the subjects of future papers.) There are strong selection effects for those WR subtypes which were used to determine the selection criteria, and as a result, no WC9 or late WN type (>WN6) stars have yet been found. Improvements now underway in survey image reduction will permit discovery of the less strongly distinguished subtypes.

3. SPECTROGRAPHIC OBSERVATIONS AND REDUCTION

The spectrographic follow-up data were taken between 2007 April 28 and June 6, with the near-infrared (0.8–2.5 μm) SIMON spectrograph (Doyon et al. 2000) of the Université de Montréal mounted on the 1.5 m telescope at CTIO. SIMON has a scale of 0.′46 pixel−1 on the CTIO 1.5 m telescope. Targets were observed in the K band with a resolving power of R ∼ 1500. Each target was observed five times, with a nod to move the target along the slit between each observation. Total integration times ranged from 10 to 30 minutes per candidate.

All data were reduced using IRAF routines. Images were dark subtracted and flat fielded to remove any instrument signature; spectra were then extracted using the APER task. This task also provided sky subtraction by fitting the background on either side of the object along the slit. The five exposures were scaled and median-combined. Standard stars, which were observed periodically throughout the night, were similarly reduced, and corrections made for Brγ absorption in the telluric standard. Object spectra were then divided by the temporally closest standard-star spectra to remove, as best as possible, the atmospheric absorption features, particularly those at 2.008 μm and 2.059 μm, and a fainter feature at 2.199 μm.

Wavelength calibrations were done using the atmospheric OH emission observed off-target by the spectrograph during each object observation. Lines were first identified using the IDENTIFY task and were compared with the coordinate list oflines.dat included therein (Steed & Baker 1979). The wavelength solution was then refitted to each observed target using the REIDENTIFY task. In general, the root-mean-square (rms) error of the residuals of wavelength fits was less than 1 Å, and in most cases between 0.1 Å and 0.3 Å. These dispersion solutions were each applied to the corresponding target object, and then corrected for the intrinsic heliocentric motion using the RVCORRECT task to identify the heliocentric velocity and the Dopcor task to Doppler shift the wavelength scale.
4. RESULTS

From our target list of 173 candidates we have discovered 41 new WR stars: 15 of type WN and 26 of type WC. Right ascension and declination, as well as $J$, $H$, and $K_S$ magnitudes, were obtained from 2MASS, and are listed in Table 2. All 2MASS objects were then referenced in NOMAD (Zacharias et al. 2005) to obtain $B$, $V$, and $R$ magnitudes, when available, which are also included in Table 2. Spectra are grouped by assigned spectral type, and are presented in Figures 1(a)–(k).

4.1. Spectral Line Measurements

The IRAF task SPLIT was used to fit the continuum and then optimize and deblend Gaussian functions to fit the observed emission lines in all spectra. This gave measurements of line centers, equivalent widths (EWs), and FWHMs.

A number of errors contribute to reduce the accuracy of these measurements. Blending of many lines creates the largest emission features, and introduces errors into line center measurements up to 10 Å. It also skews the shape of the feature to be a poor fit to a Gaussian. In general, the rms error of the residuals for the fits was about 10% of the continuum value. Additionally, the continuum was quite difficult to determine precisely due to the abundance of emission lines throughout the spectrum, especially in WC stars, resulting in errors in the equivalent width measurements. A number of our WN detections were rather faint, with peak fluxes only twice the continuum level, resulting in lower signal-to-noise ratios for these spectra. Finally, ground-based observatories must peer through the murky atmosphere, so that the strong C IV 2.08 μm line in WC stars falls on the edge of the equally strong atmospheric absorption feature at 2.06 μm. Division by a standard star removes most of this feature; however, changes in atmospheric conditions between
Figure 1. (a) WN4 spectra. (b) WN5 spectra. (c) WN6 spectra. (d) WN7-9 spectra. (e) WCE spectra. (f) WC5-6 spectra. (g) More WC5-6 spectra. (h) WC7 spectra. (i) WC9 spectra. (j) WC8 spectra. (k) More WC8 spectra.
Figure 1. (Continued)
Figure 1. (Continued)
Figure 1. (Continued)
Figure 1. (Continued)
object and standard-star observations result in residual features on the blue side of the emission line.

4.2. Spectral Classification

The strong emission lines visible in the spectra, while easily distinguished as belonging to either type WC or WN, are the result of overlapping blends of emission lines of various elements. In the optical, WR stars are categorized by looking at ratios of equivalent widths of various nitrogen species for WN, carbon and oxygen species for WC, and He II and He I for both. However, the heavy blending of lines present in the K band makes it more difficult to find either isolated spectral lines or distinguishing ratios of blended lines (Figer et al. 1997).

Spectral subtypes were assigned following Crowther et al. (2006). These are presented in Tables 3 and 4, along with the ratio of equivalent widths used for categorization. The ratio \( W_{2.189}/W_{2.165} \) was used to categorize the WN stars, and the ratio \( W_{2.076}/W_{2.110} \) was used to categorize the WC stars. Also following Crowther et al. (2006), WN stars with FWHM(He II 2.189) \( \geq 130 \) Å were classified as broad/strong, and the letter “b” appended to the subtype designation. Subtypes thus assigned are expected to be accurate to within one subtype. The 40 known WR stars were similarly assigned subtypes, which agreed within one subtype of their published spectral classifications.

Those WC stars with especially broad, heavily blended C IV and C III lines, as presented in Figure 1(e) and which match our observed spectra of WR19 (WC4) and spectra observed in Figer et al. (1997) of WR146(WC4), WR143(WC5), and WR150(WC5), are classified more generally as WCE.

4.3. Measured Line Centers

Blended lines complicate the calculations of accurate radial velocities (RVs), as there is no longer any fixed line center with which to compare theoretical and actual wavelengths. The purest line in our K-band spectra, He II at 21891 Å, allows calculation of RV with respect to the motion of the Sun in principal; however, this line is extremely weak or not discernable in most of the WC stars. Line-center measurements are further complicated by the difficulty of accurately fitting Gaussian curves to WR emission lines, as described in Section 4.1, resulting in errors of 5 Å to 10 Å in determination of peak wavelengths. This corresponds to errors on the order of 50–150 km s\(^{-1}\). In general, the direction of motion with respect to the Sun follows the clockwise rotation of the Galaxy; however, as noted, the error on these measurements is large. Measured RVs (based on the measured line centers, which may be shifted, depending on details of the line formation mechanism) for WNs and, when possible, WCs, are included in Tables 3 and 4.

5. WR DISTRIBUTION

Distances to all new WR stars were estimated from the 2MASS J, H, and K\(S\) color excesses, using the method of spectroscopic parallax described in Crowther et al. (2006). Intrinsic J \(-\) K\(S\) and H \(-\) K\(S\) colors specific to WR subtype were taken from Crowther et al. (2006) and used to calculate \( E_{J-KS} \) and \( E_{H-KS} \). Extinction ratios taken from Indebetouw et al. (2005) then allow two calculations for \( A_{K_S} \):

\[
A_{K_S} = 0.67^{+0.07}_{-0.06} E_{J-K_S}
\]
The average of these values, $\bar{A}_{K_s}$, was used to calculate the distance modulus, taking the apparent $K_S$ magnitude from 2MASS and the subtype-specific absolute magnitude, $M_{K_s}$, from Crowther et al. (2006). Derived $K_S$-band extinctions and Galactocentric distances, $R_G$, are listed in Table 5. Calculations for $R_G$ assume the IAU standard Solar Galactocentric distance $R_0 = 8.0$ kpc, and the known Galactic WR stars are on the same scale in Figure 2. Because these calculations are based on the inherent absolute magnitude and $J - K_S$ and $H - K_S$
colors for each subtype, the errors are highly dependent on the accuracy of these measurements. The measured scatter about the adopted color values is approximately 0.02 mag (Table A1 in Crowther et al. 2006), which is negligible in $A_{K_S}$ compared to the average scatter of 0.4 mag from the adopted $M_{K_S}$ values. The redundant calculations of $A_{K_S}$ also provide some indication of the reliability of our measurement. The two values are generally in agreement to within 0.2 mag, especially for the WNs, however they can differ by as much as 0.66 mag for some of the WCs, indicating that more accurate subtype specific colors and absolute magnitudes are needed. These uncertainties give typical errors on the order of 25% in our distance measurements, though they may range as high as 40% in some cases.

The distance to new stars was constrained by the limiting observable magnitude of $K_S \sim 11.5$. Using the overall average extinction $A_{K_S} = 1.4$, we can calculate the typical measurable distances by subtype. As all discovered WN stars were early types, we can distinguish the faintest observed, strong and weak-lined WN as having average distances of 8.0 and 9.4 kpc, respectively, while observations of the faintest WC stars yield typical distances of 8.9 kpc.

In Figure 2, our new WR stars (in bold) have been overplotted with the previously known WRs onto the plane of the Galaxy, with distances to the known stars taken from the seventh catalog of Galactic WR stars (van der Hucht 2001). The Galactic center is labeled, and circles of radius 4, 8, and 12 kpc are plotted. The new WR stars largely follow the distribution pattern established by the known stars, though we can see that we are beginning to push out to larger heliocentric distances. We also find new stars without optical counterparts within a few kpc of our Sun, reinforcing the necessity of WR surveys in the near infrared.

Conti & Vacca (1990), along with the more recent reanalysis in Hadfield et al. (2007), maintain that WR stars trace the spiral structure of the galaxy. One arm may be seen along roughly the 8 kpc radius, and an inner arm can perhaps begin to be traced along the inner 4 kpc radius. However, the distance error bars are not trivial, so that firm conclusions about the utility of WR stars as spiral tracers should not yet be drawn.

### 6. CONCLUSIONS

We have discovered 41 new Galactic WR stars, 15 of type WN and 26 of type WC, using a new, near-infrared narrowband survey of the Galactic plane. The reduced extinction from dust and gas in the near-infrared makes this the optimal method for future discovery of the thousands of undetected Galactic WR stars. Of the 254 total candidates observed spectrophotographically, 75 proved to be emission line objects. All of the emission line objects that
were not WR stars (34 objects) were planetary nebulae (PNe). As the key goal of this survey is the detection of new Galactic WR stars, we amended our selection criteria to eliminate likely PN. Our modified selection criteria yielded 173 WR star candidates which were observed spectrographically: 41 proved to be new WR stars. With such a 23% detection rate, we have barely scratched the surface of the wealth of new WR stars expected to be discovered within our survey area with the available data.

An initially fairly simple sky-subtraction methodology resulted in relatively scattered color–magnitude diagrams, raising our cut for emission objects to 5σ. It also meant that most of our nondetections were erroneously selected objects with featureless spectra. Improved sky subtraction (using entire nights of data, median-filtered in each filter as skyflats) will allow us to lower this limit to 3σ and will improve the detection rate of emission-line objects. We expect this survey to yield thousands of additional discoveries in the coming years.

Our survey limits will be pushed fainter by the use of a larger infrared telescope for spectroscopic follow-up. As we increase the number of known stars, we will also increase the statistical significance of distribution plots, and subtype abundances, allowing us to learn more about our Galaxy’s structure and composition. The Galactic center is expected to prove an especially rich area for discovery, but it is still largely terra incognita as the crowding of stars there is very high. The vast majority of Galactic WR stars remain to be discovered, but we now have a proven technique to continue the search.

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**APPENDIX A**

**SUMMARY OF KNOWN WRS CONTAINED IN SURVEY IMAGES**

In Tables 6 and 7, we give a summary of the emission line Δm values measured for the known WRs found in the survey area. All survey stars were compared with finder charts for the known WR stars to ensure that photometric measurements were made for the correct star. All stars were found by eye to be present in the survey images, though some had not been identified photometrically due to nebulosity and occasional out-of-focus images.

The Δm magnitude for each narrowband filter gives the difference in magnitude from the interpolated continuum magnitude. Negative values of Δm indicate emission, positive values indicate absorption for lines in the narrowband emission-line filter, assuming there are no other problems. Several fields were imaged multiple times, and on more than one night. This allowed us to estimate the accuracy of the emission line magnitudes in Tables 6 and 7 as ±0.03 mag.

**APPENDIX B**

**THE TOTAL NUMBER AND DISTRIBUTION OF GALACTIC WR STARS**

Following Shara et al. (1999), we assume that the star distribution expressed in cylindrical galactic coordinates (i.e., $N(r, l, z)$) follows that of the interstellar dust and adopt an axisymmetric exponential disk formulation with an outward flair taken from Drimmel & Spergel (2001):

$$N(r, l, z) = N_o e^{-\frac{(R - R_o)}{\lambda}} \sec h^2 \left( \frac{z - z_o}{\lambda H_o(R)} \right).$$

With,

$$R(r, l) = \sqrt{r^2 + R_o^2 - 2rR_o \cos l}.$$

A linear flair is added by imposing the following functional
Figure 3. Contour plot of the target $K$ magnitude in order to detect 95% of all WR stars along a line of sight. The inner contour represents a magnitude higher than 17 and each contour represents intervals of 1 mag.

(A color version of this figure is available in the online journal.)

Figure 4. Number of WR stars along a line of sight within a Capir field ($35' \times 35'$). The inner contour represents 40 WR stars per field and each contour represents intervals of 5 WR stars per field. According to this model, ~5600 of all WR stars (i.e., 88%) should be found within the region: $l = 320$ to 400 and $b = -1$ to 1.

(A color version of this figure is available in the online journal.)

form to $\alpha_{Ho}$:

$$\alpha_{Ho}(R) = \left[ \frac{h_o + (R(r, l) - r_f)h_1}{h_o} \right] \cdot \begin{cases} R(r, l) > r_f, \\ R(r, l) \leq r_f. \end{cases}$$

In these equations, $N_o$ is the local stellar density, $R_o = 8000$ pc and $z_o = -17$ pc are respectively the solar galactocentric distance and distance from the galactic plane. The scale length $\alpha_{R_o}$ and the constants $h_o$, $h_1$, and $r_f$ which define the scale height $\alpha_{Ho}$ are taken from the fit to the FIR emission of the interstellar dust of Drimmel & Spergel (2001) and are respectively 2260 pc, 134 pc, 0.015 and 4400 pc.

Although the assumption that the star distribution follows the dust is justified for O stars, it must be modified for WR stars to account for the observed metallicity dependence of their galactic distribution. Using the results of Maeder & Meynet (1994) for the metallicity dependence of the WR/O number ratio and the radial metallicity distribution of the galactic disk from Smartt & Rolleston (1997), Shara et al. (1999) found that the WR star density can be expressed as

$$N_{WR}(r, l, z) = N_{WR_o} e^{-\frac{R(r, l)}{\alpha_{RWR}}} \cdot \sec^2 \left( \frac{z - z_o}{\alpha_{Ho}(R)} \right),$$

where,

$$\alpha_{RWR} = \frac{1}{\alpha_{R_o}} + 7 \times 10^{-5} \ln 10 = 1657 \text{ pc}.$$  

Knowing the local surface density of WR stars from van der
Figure 5. Number of WR stars along a line of sight within a CPAPIR field up to a magnitude $K = 15$. The inner contour represents 35 WR stars per field and each contour represents intervals of 5 WR stars per field. (A color version of this figure is available in the online journal.)

Hucht (2001)

$$\int_{-\infty}^{\infty} N_{WR}(0,0,z) \, dz = 2.87 \times 10^{-6} \text{ pc}^{-2}.$$ 

And applying this constraint to $N_{WR}(r,l,z)$ we obtain

$$N_{WR} = \frac{2.87 \times 10^{-6} \text{ pc}^{-2}}{\int_{-\infty}^{\infty} \text{sec}^2 \left( \frac{z-z_0}{a_{HD}(0)} \right) \, dz} = 2.09 \times 10^{-8} \text{ pc}^{-3}.$$ 

Finally, the conversion of the WR star density from a spatial ($N_{WR}(r,l,z)$) to a magnitude ($\eta_{WR}(m,l,z)$) dependence is done in two steps. First, we use the conservation of stars in both systems to write

$$\eta_{WR} \, dm \, dl \, dz = N_{WR} \, dr \, dl \, dz.$$ 

Then, the radial distance $r$ is converted to the magnitude $k$ using the inverse square law of light attenuation accounting for interstellar extinction:

$$5 \log r - 5 = k - M_k - \int_{0}^{r} a_k(r,l,z) \, dr,$$

where the extinction $a_k(r,l,z)$ allowing for a spherical hole in the interstellar dust at the center of the Galaxy is (see Drimmel & Spergel 2001)

$$a_k(r,l,z) = \begin{cases} a_{k_0} e^{-\frac{(R_{HD}(r,l)}{a_{HD}(0)}} \text{sec}^2 \left( \frac{z-z_0}{a_{HD}(0)} \right) & R(r,l) \geq 0.5 R_o, \\ a_{k_0}(0.5 R_o, l, z) e^{-\frac{(R_{HD}(r,l)}{a_{HD}(0)}} & R(r,l) < 0.5 R_o, \end{cases}$$

with $a_{k_0} = 1.08 \times 10^{-4} \text{ mag pc}^{-1}$ (Mathis 1990) and the intrinsic magnitude of WR stars in the $K$-band $M_k = -4 \text{ mag}$ (van der Hucht 2001).

These equations have been solved numerically to determine the star density $\eta_{WR}(k,l,z)$ to an accuracy better than 1% using a Monte Carlo method with a Sobol quasi-random number generator in three dimensions. By integrating over the whole Galaxy the model predicts $\sim 6400$ WR stars which is very close to the 6500 predicted by van der Hucht (2001).

Further validation can be carried out by applying this model to the $V$ band where most WR stars have been detected so far. It is then possible to compare the observed to the predicted number of WR stars. To do so, we adopt $M_V = -5 \text{ mag}$ (van der Hucht 2001) and $a_{V_0} = 1.0 \times 10^{-3} \text{ mag pc}^{-1}$. According to the model, the number of WR stars observable up to a magnitude of $V = 15, 12,$ and 10 are respectively 153, 79, and 42. These numbers are very close to the respective observed numbers reported by van der Hucht (2001) of 159, 80, and 36. It is again apparent how important it is to continue the search for new WR stars in the infrared.

Figure 3 shows the contour plot representing the necessary target $K$ magnitude to detect 95% of all WR stars along a line of sight. Figure 4 shows the number of WR stars expected per CPAPIR field and Figure 5 presents the same information for $K \leq 15$. Figure 6 shows the cumulative number of expected Galactic WR stars as a function of $K$ magnitude. At $K = 11, 12, 13, \text{ and } 14$, the expected numbers of Galactic WR stars are 1200, 2500, 4200, and 5400.
Figure 7. Finder charts for WR stars in Table 2.
Figure 7. (Continued)
### Table 1: WR Stars Identified in the Survey

| Object Number | RA (h:m:s) | DEC (°:°:°) | Observed JHK | Observed JHK | Observed JHK |
|---------------|------------|-------------|--------------|--------------|--------------|
| 1096_22 WC8   | 17h:22m:41s| -59°:0m:36s| 10.73        | 15.43        | 10.54        |
| 1222_15 WC8   | 17h:22m:41s| -59°:0m:36s| 10.73        | 15.43        | 10.54        |
| 1385_24 WC8   | 16h:38m:42s| -60°:2m:12s| 10.73        | 15.43        | 10.54        |
| 956_25 WN4b   | 15h:31m:30s| -59°:2m:12s| 10.73        | 15.43        | 10.54        |
| 979_11 WN6b   | 15h:20m:36s| -59°:2m:12s| 10.73        | 15.43        | 10.54        |
| J= 13.84      | H= 11.83   | K= 10.64    |              |              |              |
| J= 13.88      | H= 12.15   | K= 11.06    |              |              |              |
| J= 10.96      | H= 9.936   | K= 9.056    |              |              |              |
| J= 10.26      | H= 8.973   | K= 8.097    |              |              |              |
| J= 15.05      | H= 12.79   | K= 11.54    |              |              |              |
| J= 13.28      | H= 11.76   | K= 10.73    |              |              |              |

### Figure 7 (Continued)

The table continues with more stars and their observational data.
**APPENDIX C**

**FINDER CHARTS**

We present in Figures 7(a)–(g) the finder charts for the 41 new WR stars discovered in our survey.

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