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A Robotic Wide-Angle Hα Survey of the Southern Sky

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ABSTRACT

We have completed a robotic wide-angle imaging survey of the southern sky ($\delta = +15^\circ$ to -90°) at 656.3 nm wavelength, the Hα emission line of hydrogen. Each image of the resulting Southern H-Alpha Sky Survey Atlas (SHASSA) covers an area of the sky 13° square at an angular resolution of approximately 0.8 arcminute, and reaches a sensitivity level of 2 rayleigh (1.2×10^{-17} erg cm^{-2} s^{-1} arcsec^{-2}) per pixel, corresponding to an emission measure of 4 cm^{-6} pc, and to a brightness temperature for microwave free-free emission of 12 μK at 30 GHz. Smoothing over several pixels allows features as faint as 0.5 rayleigh to be detected.

Subject headings: surveys—instrumentation: miscellaneous—techniques: image processing—ISM: structure—H II regions—cosmic microwave background

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1. Introduction and Scientific Purpose

Early surveys of the Milky Way, such as those of Barnard (1927), photographed several regions of interstellar gas ionized by the ultraviolet radiation of nearby hot stars. Many other surveys were done over the ensuing decades (see the list of references given by Sivan (1974)). However, it was not until after the discovery of pulsars (Hewish et al. 1968) that it became generally recognized that ionized hydrogen is a pervasive component of the interstellar medium. Soon thereafter Sivan (1974) conducted a photographic survey in search of this general diffuse medium, reaching a limiting brightness of 15 rayleigh ($1\ \mathrm{R} = 10^6/4\pi$ photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1} \Leftrightarrow \mathrm{EM} \approx 2\ \mathrm{cm}^{-6}$ pc), corresponding to an emission measure of about 30 cm^{-6} pc, and covering the band of latitude $|\mathrm{b}| < 25°$ at a resolution of approximately $10'$. Somewhat later, Parker, Gull, & Kirschner (1979), using an image tube camera, published an atlas of images in four emission lines ([Sll], Hα+[NII], O[III], Hβ) and the blue continuum (422 nm), covering the region $|\mathrm{b}| < 8°$, reaching a surface brightness ($\approx$ 15 R) about the same as that of Sivan's survey, at an angular resolution of $0\overset{'}{.}6$. Of course the Hα line is included in the pass band for the red plates of the National Geographic Society/Palomar Observatory Sky Survey (POSS 1), and these show many prominent emission nebulae, those brighter than approximately 100 R. (The ESO/SRC Southern Sky Atlas is similar, but goes a bit deeper.) The second generation plates (POSS 2) go about a factor of four fainter, reaching a level of approximately 25 R.

Two difficulties with these photographic surveys are that their sensitivity is low, and because of the non-linear response of photographic emulsions and contributions from continuum radiation it is difficult to derive quantitative intensity information from them. Modern CCD detectors, on the other hand, are intrinsically linear, have high quantum efficiency, and allow for digital subtraction of continuum images. Although photographic surveys still have their place (Parker & Phillipps 1998), most modern studies are done via narrow-band CCD imaging or Fabry-Perot spectroscopy. An early example of the former technique is the work of McCullough, Reach, and Treffers (1990), who surveyed the region $l = 120°$ to $190°$, $b = -30°$ to $+15°$ to a level of 4 R (8 cm^{-6} pc) at 2 arcminute resolution. An early example of the Fabry-Perot technique is the work of Reynolds, Scherb, & Roesler (1973) who observed several regions with a Fabry-Perot spectrometer. Reynolds and his collaborators have recently completed a survey of the northern sky with a Fabry-Perot instrument called the Wisconsin H-Alpha Mapper (WHAM) (Reynolds et al. 1998; Haffner et al. 2001a,b). A group at Virginia Polytechnic Institute (Dennison, Simonetti, & Topasna 1998) have begun a narrow-band survey of the northern hemisphere with an imaging camera similar to ours. We present a comparison of these other surveys with our own in Section 6.2.

Both of these narrow-band imaging surveys are complementary to Reynolds' Fabry-

Perot survey, not competitive with it. Our angular resolution is 75 times better than that of WHAM. The WHAM spectrometer, on the other hand, goes ten times fainter. It also has high spectral resolution (0.026 nm, 12 km s^{-1}), and thus provides velocity as well as intensity information that the narrow- band imaging surveys cannot. Perhaps as important, the high spectral resolution allows the WHAM instrument to separate interstellar Hα emission from that coming from the Earth's geocorona and thus determine absolute intensities, whereas the images provided by the narrow-band surveys all contain an offset due to geocoronal emission (as well as telluric OH emission), an offset which is variable both temporally and spatially. In Section 5 we describe a technique for correcting our images for geocoronal emission that uses WHAM observations as fiducial points in those parts of the sky where our surveys overlap.

We present this survey to the astronomical community as a resource which we hope will find many applications. We anticipate its use in two major areas of study: first, the structure of the interstellar medium, and second, the characterization of the Galactic microwave foreground.

The survey will provide detailed information on the structure of the diffuse, warm, ionized component of the interstellar medium, information necessary for understanding the dynamics and evolutionary history of the interstellar gas. Since the survey covers the entire sky south of $+15^\circ$ declination, has higher angular resolution and reaches a fainter intensity level than does any previous large scale survey, we expect a detailed examination will show several new structures, such as stellar wind bubbles, supernova remnants, bow shock nebulae, planetary nebula shells, and other interesting objects. Some examples are noted in Section 6.4.

Even where specific Hα emission features are not seen, the survey images should be scientifically useful. Since the production of both kinds of emission results from the interaction of a proton with an electron, the ratio of intensities of free-free and Hα emission depends primarily on quantum-mechanical factors, with only a slight dependence on temperature and no dependence on density (Valls-Gabaud 1998):

$$\frac{T_b^{ff}[mK]}{I_{H\alpha}[R]} = 10.4\nu^{-2.14}T_4^{0.527}10^{0.029/T_4}(1+0.08) \tag{1}$$

where ν is the observing frequency in GHz, T_4 is the temperature of the gas in units of 10^4 K, and the second term in the last factor (1+0.08) is the relative abundance of helium. Thus our Hα images will allow accurate measurement of anisotropies in the Galactic free-free emission at microwave wavelengths (or proof that these are negligible), emission which must be subtracted from satellite or ground-based measurements to obtain the spatial spectrum of the true cosmic background radiation. In an early pilot study for this project (Gaustad et al. 1996) we showed that no more than 7% of the 44 μK anisotropy in the CMBR measured in the

Saskatoon experiment (Netterfield et al. 1995) could be due to contamination by Galactic free-free emission. The high angular resolution of our survey may be important given the discovery of a third acoustic peak in the microwave background spectrum at angular scales of about $0\overset{\circ}{.}2$ (Seife 2001), well within the range of spatial frequencies we sample. A general review of the implications of Hα observations for studies of the cosmic microwave background can be found in McCullough et al. (1999).

2. Instrumentation and Observational Procedure

2.1. Camera, Telescope Mount, and Dome

Our CCD camera, from SpectraSource, Inc., contains a 1024 x 1024 Texas Instruments chip with the following characteristics: 12-μm pixels, full-well capacity 80 Ke, quantum efficiency 62%, gain 1.4 e ADU^{-1}, and readout noise 18 e. It is cooled thermoelectrically to about -35°C, yielding a dark current of 0.04 e s^{-1}. In a 20-minute exposure, the maximum we use, the dark level amounts to about 34 ADU (48 e), about 10% the level of our typical exposures. Laboratory measurements showed that the chip response was linear up to the full-well capacity (80,000 e $\approx$ 60,000 ADU), but the variance increased non-linearly above 20,000 ADU (28,000 e). Except for some very bright objects, our exposures yield values well below this limit.

The sky is imaged onto the chip with a 52-mm focal length Canon lens operated at f/1.6, yielding a field of view of $13^\circ \times 13^\circ$ and a scale of $47\overset{''}{.}64$ pixel^{-1}.

The camera is attached to a Byers Series 2 German mount with microstepping motors on each axis. The pointing accuracy is better than $5''$ up to a zenith distance of 75°. The unguided tracking accuracy is better than $2''$ hr^{-1}. Thus, with $48''$ pixels, no external guider is needed.

The system is housed in a 10-foot dome (from Technical Innovations, Inc.) on a concrete pad located near the 1-meter telescope building at Cerro Tololo Inter- American Observatory (CTIO). The small size of the instrument and dome has caused the CTIO staff to give our instrument the nickname of El Enano—The Dwarf. We added magnetic microswitch sensors, power relays, and a position encoder to the dome system so that it could be controlled by a computer. We also added a third dome rotation motor, replaced some plastic parts with metal, and modifed the shutter cable system in order to improve reliability of the dome operation. A Texas Weather Instruments weather station completes the system. Two PCs running scheduling and control programs written in Visual Basic under Windows 95 control the camera, mount, dome, weather station, and light box. They communicate with each other and with the outside world via Ethernet using standard TCP/IP protocol.

We are grateful to Las Cumbres Observatory, Inc., for loaning us much of this equipment for the duration of the project.

Because the twilight sky is not uniform over our wide field of view (Chromey & Hasselbacher 1996), we do not use sky flats for calibration. Instead we use a lightbox containing a translucent screen illuminated by incandescent light bulbs and by hydrogen emission lamps.

2.2. Filters

A filter wheel mounted between the lens and the sky contains an Hα filter of 3.2-nm bandwidth and a dual-band notch filter, which excludes Hα but transmits two 6.1-nm bands of continuum radiation on either side of Hα, centered at 644 nm and 677 nm (Figure **??**). Both filters were obtained from Custom Scientific, Inc.

The choice of the Hα filter bandwidth was governed by two considerations. We want a narrow bandpass to reduce the foreground sky continuum, but large enough that transmission losses near the edge of the field are small. Because our filter is placed in front of the camera lens, light imaged at any point on the detector enters the filter as a parallel beam at an angle of incidence equal to the angular distance of the point from the optical axis. For a simple interference filter (multi-layer filters are somewhat more complicated) the central wavelength at angle of incidence θ is given by the formula (Smith 1990)

$$\lambda = \lambda_o \sqrt{1 - \frac{\sin^2\theta}{n^2}} \tag{2}$$

where n is the index of refraction. The filter band shifts towards the blue with increasing angle of incidence; equivalently, a line shifts towards the red with respect to the filter central wavelength, and moves to a different part of the filter transmission curve. For $\theta = 9^\circ$, near the corners of our images, the wavelength shift at 656.3 nm is approximately 1.0 nm. We have therefore chosen a filter with 1.6 nm half-width.

The central wavelength of an interference filter shifts to longer wavelengths with increasing temperature, in our case about 0.03 nm $^\circ$C^{-1}. The filter wheel is encased in styrofoam and maintained at a constant 25 °C temperature to minimize such temperature-related shifts and to inhibit moisture from condensing on the filters or the lens. The temperature is deliberately set higher than the design temperature of 20 °C, and higher than the night- time ambient temperature, so that a) only active heating, not cooling, is needed to maintain the temperature; b) the bandpass is shifted slightly to the red of Hα at the center of the field, thus reducing the variation in transmission with angle of incidence as the central wavelength shifts blueward towards the edge of the field; and c) the possibility of condensation on the lens is eliminated. The transmission of 656.3 nm light as a function of angle of incidence, as measured on our lightbox while illuminated by a hydrogen emission lamp, is shown in Figure **??**.

Figure **??** also shows the position of atmospheric OH emission lines and interstellar emission lines. The Hα band (653.3 - 659.3 nm for T/T$_{max}$ > 10%) contains only five lines of the 6-1 band of OH. But some of these, particularly the 655.4 nm line, may make a significant contribution to the general foreground level, comparable to that from geocoronal Hα. To the extent that this foreground emission can be modelled as a 2-dimensional plane, it is removed from our final images by the methods discussed in Sections 3.4 and 5. In addition, the interstellar emission lines of [NII] at 654.8 and 658.3 nm lie within the Hα filter band. The filter transmission is approximately 39% and 26% respectively at these wavelengths (at the operating temperature of 25 °C) compared to the transmission at Hα of 78%. In some astronomical objects, the [NII] lines are comparable in strength to Hα, so this contamination by [NII] lines should be taken into account in any careful quantitative measurements of the atlas images. For example, if the 658.3 line has the same intensity as Hα and the 654.8 nm line has 1/3 that strength (the ratio of the two [NII] lines is always 1/3), about 33% of the brightness measured in the Hα pass band is really [NII] emission, not Hα. (See also the discussion of the [NII] lines in Section 4.)

The continuum filter bands were chosen primarily to avoid emission lines in the night sky (Broadfoot & Kendall 1968; Osterbrock & Martel 1992; Osterbrock et al. 1996). The 644 band falls longward of the stronger lines of the 9-3 band of OH and excludes most of the short wavelength lines of the 6-1 band of OH, as well as excluding the OI lines at 630.0 and 636.4 nm. The 677 band falls between the 6-1 and 7-2 bands of OH, and excludes the interstellar lines of HeI at 667.8 nm and of [SII] at 671.6 nm. The transmission at the wavelength of the [SII] line at 673.1 nm is only 16%, though it will be somewhat higher, up to 70% , at high angles of incidence. In many astronomical objects this line is less than 10% the strength of Hα, though it can be of comparable strength in shocked regions, such as in supernova remnants, and in the very faint emission from the warm interstellar medium (Haffner, Reynolds & Tufte 1999). The exposure times used for the continuum exposures are four times shorter than for the Hα images, so the contamination from the [SII] 671.6-nm line is probably no more than a few per cent in most regions, though it may be as high as 25% in strongly shocked regions which appear near the edges of our fields.

2.3. Computer Control

One of the robot's computers positions the telescope and dome while the other operates the camera, schedules the observations, and runs the ftp and email communication links. A log of the night's operations and sample images are sent to the PI each morning via email and ftp, but the full data set is recorded on disk and then transferred to DAT tape during the day. We can inquire of the status of the robot and modify its observing schedule via email, and make changes in the control programs via ftp. But we do not operate the camera in real time–it is a true robot, in the sense that its real-time operations are autonomous . The robot monitors the weather station continuously, and will not attempt observations if humidity or wind conditions exceed safe limits, but as an extra precaution it also asks permission (via email) of the 4-meter telescope operator before opening the dome. The operator can also close the dome via email command. The only other human intervention, during normal operations, is for weekly tape-changing and preventive maintenance.

2.4. Observational Procedure

All observations are taken in a dark sky, after the end of evening twilight and before the beginning of morning twilight, and with the moon below the horizon. A normal set of science observations consists of five 20-minute exposures through the Hα filter interspersed among six 5-minute exposures through the dual- band continuum filter. Use of multiple exposures allows removal of cosmic ray events and other transients, such as meteor, satellite, and airplane trails. Interspersing the Hα and continuum exposures helps compensate for changes in sky foreground levels with time or zenith distance.

Reflective ghosts of bright stars appear in the images. These are caused by light focused at a point on the CCD surface reflecting back through the lens to the filter, where it is again reflected and focused at a different point on the detector. To assist in identifying and removing the reflective ghosts, the camera pointing is dithered in a raster pattern of $1/4^\circ$ steps between each exposure. The ghosts move in the opposite direction to the stars themselves and so can be readily identified in the reduction procedure. (Transmissive ghosts are produced by small angle scattering off of imperfections in the filter. These move in the same direction as the stars during dithering, and so cannot be simply identified and removed during processing.)

Between observations of each science field, we take a few exposures pointed at the pole to obtain data on changes in extinction during the night. We also take occasional short exposures of bright standard objects.

The program that schedules the observations gives priority to fields at large hour angle and high (more northerly) declinations, those for which the observing window is smallest. Before observing more easterly fields it attempts to observe those fields which are about to become unavailable in the west. The program does not schedule an observation if the beginning or ending zenith distance would be greater than 65°. Because the camera is on a German mount, which must be flipped 180°at the meridian, observations are scheduled so they can be completed without crossing the meridian. Overall, 45% of the fields were observed in the western part of the sky and 55% in the east.

Biases, darks, and flats are taken during twilight at the beginning and end of each night. Each time we normally record 15 biases, five darks each of 20 minute duration (to match the maximum exposure times of the science images), and five flats for each of the two filters with the light box illuminated by two sets of incandescent lamps and for the Hα filter with the light box illuminated by two sets of hydrogen emission tubes. The exposure times for the flats were adjusted to give images with a mean brightness several thousand times the readout noise, but below the level where the variance of the detector noise becomes non-linear.

2.5. System Performance

The system noise is a combination of photon noise from the sky foreground (with a small contribution from Hα line emission), dark current noise, and readout noise. We can calculate the expected noise on a single exposure from the following formula:

$$N = \frac{1}{G}\sqrt{[\beta(I_{H\alpha} + S_\lambda \Delta\lambda)A\Omega TQ + D]\tau + \sigma_R^2} \tag{3}$$

where N is the noise level (ADU), G is the gain (e ADU^{-1}), β is the conversion factor of Rayleighs to photon intensity at 656.3 nm (6.7×10^{-3} photons s^{-1} cm^{-2} arcminute^{-2} R^{-1}), $\mathrm{I_{H\alpha}}$ is the intensity in the Hα line (R), S_λ is the specific intensity of the sky foreground (R nm^{-1}), $\Delta\lambda$ is the bandwidth of the filter (nm), A is the area of the lens (cm^2), Ω is the solid angle of the sky focused on one pixel (arcminute^2), T is the transmission of the optical system, Q is the quantum efficiency, D is the dark current (e s^{-1}), τ is the integration time (s), and σ_R is the readout noise (electrons).

Using the parameters given in Section 2.1, a value of 10 R for the brightness of the geocoronal Hα line (Nossal et al. 1993), S_λ = 13 R/nm (Broadfoot & Kendall 1968) for the specific intensity of the sky foreground, an assumed value of T = 0.6 (for the combined transmission of lens, filter, and CCD window), filter bandwidths of $\Delta\lambda$ = 3.2 nm and 12.2 nm for the Hα and continuum filters respectively (Section 2.2), and τ = 1200 s and 300 s for the integration times of the Hα and continuum exposures (Section 2.4), we get expected noise values of 25 ADU for a single Hα exposure and 22 ADU for a single continuum exposure. Typical noise values actually achieved are 30 ADU and 24 ADU respectively, in reasonable agreeement with expectation. Note that for the above parameters the contribution to the noise from photons is larger than the detector readout noise, as desired, but only by a factor of two. The noise contributed by the dark current is completely negligible.

The expected signal, after subtraction of the dark current, can be calculated from the formula:

$$S = \frac{\beta}{G}(I_{H\alpha} + S_\lambda \Delta\lambda) A\Omega T Q \tau. \tag{4}$$

It follows that the intensity scale factor f, the number of ADU corresponding to an intensity of 1 R, is given by

$$f = \frac{S}{(I_{H\alpha} + S_\lambda \Delta\lambda)} = \frac{\beta}{G} A\Omega T Q \tau. \tag{5}$$

With the same parameters as used above for calculating the expected noise, we would predict an intensity scale factor of 11.2 ADU R^{-1} for a 20-minute exposure. The actual value, determined from observation of planetary nebulae (Section 4) is 6.8 ADU R^{-1}, a difference of 40%. One or more of the factors A, Ω, T, or Q may be overestimated, but if these estimates are reduced in order to generate better agreement between the expected and measured intensity scale factors, then the discrepancy discussed above between the expected and measured noise would increase. Perfect agreement cannot be expected for such *ab initio* calculations, and we conclude that the system in the field performs reasonably close to expectations.

After co-adding the images (Section 3), the noise is less. A typical value on the continuum-subtracted image (Section 3.3) is 14 ADU (2 R), and on the images smoothed with a 5 pixel median filter (Section 3.5) it is 5 ADU (0.7 R). Large scale features of sub-Rayleigh intensity are visible on several images. We estimate that the faintest feature visible on our images has a brightness of approximately 0.5 rayleigh.

Although the aim of this survey is the discovery and study of objects emitting at the Hα line, there may be some applications in which the continuum point sources (stars) are of interest. The limiting R-magnitude on the co-added images is about 14.8 at b = $-90°$, deteriorating (because of confusion) to R = 12.5 at b = $20°$.

As mentioned in Section 2.4, we took short exposures of the south celestial pole region before and after each set of science images. Aperture photometry of several stars on these polar images showed that variations in extinction during one night or from night to night (for those nights for which data appears in the atlas) rarely exceeded 0.1 mag (10%).

Similarly (Section 2.4), we observed regions containing bright standard objects on most nights on which data appearing in the atlas were obtained. We measured the brightness of carefully selected standard regions on these images. For those standard objects which were observed over a large range of elevations, we derived an average extinction coefficient of 0.082 mags airmass^{-1} at 656.3 nm, compared to the standard extinction for CTIO at this wavelength of 0.096 mags airmass^{-1} (Stone & Baldwin 1983). The difference is within the seasonal and night-to-night variations of extinction at CTIO (Hamuy et al. 1992, 1994). None of our data were obtained at zenith distances greater than 65°, an air mass of 2.4 and extinction of 0.2 mag (20%), and most images were observed much closer to the zenith. Again, individual intensities obtained on particular nights never differed by more than than 0.1 mag (10%) from that expected for the zenith distance at the time of observation.

Both the studies of the polar images and the standard objects indicate that variations in extinction do not affect the brightness of our images by more than 10%. Therefore we have made no attempt to correct our data for atmospheric extinction.

3. Data Processing

3.1. Calibrations

Co-adding of the calibration exposures (biases, darks, and flats) is done on site automatically, with the medians of evening and morning sets recorded separately. These, and all science images, are recorded on tape and shipped to Swarthmore for later processing. No significant differences between morning and evening calibration images were detected, and these were simply averaged, if both existed.

The science images were corrected for bias and dark current in the usual way and then divided by the flat field image appropriate to each filter, normalized to the mean flat value of the central 100 pixel × 100 pixel area.

Early in the project we assumed that the lightbox was uniformly illuminated and emitted light at a constant brightness in all directions. We then attributed an observed decrease in brightness of the flats near their edges to vignetting in the camera system. However, using the flats as observed caused a rise in brightness of both the Hα and continuum images near their edges, leading us to conclude that the lightbox emission was not truly isotropic, but decreased in intensity with angle to the normal. We do not know the origin of this effect, but suspect it may be caused by nonsymmetric scattering properties of the plastic diffuser screens. We corrected for this effect by determining the average of each flat image at constant radial distances from the center, and dividing the flat by this circularly symmetric function. Such a procedure preserves the features in the flat image due to pixel-to-pixel gain differences and to such things as dust specs on the camera window, but any symmetric features (such as true vignetting or gain variations which are a function of distance from chip center) are not corrected for and may propagate into the final images. However, examination of the continuum images at high galactic latitude ($|b| > 40°$), where there are no bright features, shows that on average they are flat to within ±3% (1.3 R) out to 8°.0 from the center (see Figure **??**), indicating that such vignetting-type effects, if they are present at all, are fairly small.

3.2. Co-addition of Science Images and Removal of Ghosts and Transients

The sets of six continuum and five Hα images are aligned and coadded separately, pixel by pixel, after removing transients produced by cosmic rays, meteors, airplanes, and satellites. We characterize a value as an outlier, to be excluded from the co-addition, if it lies more than 3.5 times the standard deviation from the mean.

Given the nature of our data, determining the mean and standard deviation is not completely straightforward. First, since we have a small number of values contributing to each pixel (five or six), one of which (if influenced by a transient event) may differ by a large amount from the others, a straight average may not give a good estimate of the mean. Likewise, the rms average of the deviations from this mean may not give a good estimate of the standard deviation. Therefore we choose to take the median rather than the straight average as an estimate of the mean, and the median of the absolute deviation from this median as an estimate the standard deviation.

A further complication is that each image is taken at a different zenith distance and therefore will contain a different airglow and geocoronal contribution to the foreground level. The offsets due to these differences are much larger than the noise. Therefore the median of pixels from the original set of images would give the value of the middle image, with no averaging of the noise. Likewise, the median of the absolute differences from this median would overestimate the standard deviation, for it would include the offsets as well as the variations due to noise.

The first step, therefore, is to make corrections for the differences in foreground level. We assume that the continuum images consist of a galactic (and extragalactic) component C_g plus a foreground component C_{for} which varies with time:

$$C_{obs} = C_{for}(t) + C_g. \tag{6}$$

Because the spatial transmission function of the Hα filter (Figure **??**) is still included in the line contribution to the Hα images at this stage (it is removed later in the processing—see

Section 3.3), the corresponding relation for the Hα images is a little different:

$$H_{obs} = 1.2[C_{for}(t) + C_g] + T_H[H_{for}(t) + H_g] \tag{7}$$

where H_g is the galactic contribution to the Hα line, H_{for} is the time-variable foreground (geocoronal) contribution to the Hα line, and T_H is the spatial transmission function for the Hα line. The factor 1.2 accounts for the different filter bandwidth and exposure times for the Hα images compared to the continuum images, and is the average of the factors needed to match star intensities during the continuum subtraction process (Section 3.3). Note: Equation 7 does not account for the contribution of telluric OH line emission (Section 2.2) to the Hα images, for which a different spatial transmission function should be used. To the extent that these lines are important, the separation of the line and continuum components of the Hα image is only approximate.

We first determine the average brightness level, $C_{obs,n}$ or $H_{obs,m}$, of the central 800 × 800 pixel area of each image [using the "SKY" procedure of the IDL DAOPHOT package (Stetson 1987; Landsman 2001)]. For the n^{th} continuum image, we simply add a constant $C_{obs,1} - C_{obs,n}$ to bring it to the brightness level of the first image of the set. For the Hα images, we use the function $C_{for}(t) + C_g$ determined from Equation 6 and from the $C_{obs,n}$ values to interpolate the first term of Equation 7 to the time of each Hα observation. Subtracting this term from the observed brightness level $H_{obs,m}$ gives the line contribution to the brightness level, the second term of Equation 7, and thus the function $H_{for}(t)$. It is then a simple matter, using Equation 7, to correct each image to the brightness level at the time of the first image. This procedure should compensate for linear changes in airglow and geocoronal level with observation time, at least within the time frame of a particular set of images. (In Section 5 we discuss a procedure for matching levels of *all* images.) Since all the images of the set now have the same average value, medians of the image values at each pixel and medians of the absolute deviation at each pixel should give a good estimate of the mean and standard deviation.

Next, reflective ghosts are identified and marked on each image. This procedure could not be completely automated because of a random variation by several pixels of the position of the axis of reflection from image to image. This is probably due to an imperfect constraint of the plane of the filter wheel or a slight looseness of the filters in their mounts.

An empirical study of a few images showed that the ghosts are about 0.05% of the brightness of the stars, so that only the very brightest stars, those with central brightness exceeding the full-well capacity of the chip (80,000 e ≈ 60,000 ADU), produce ghosts on an image greater than the noise. In the ghost-removal procedure, an approximate axis position is assumed, the positions of the ghosts of the brightest stars calculated and marked on the image display, and the axis position adjusted interactively until the marked positions coincide with the real ghost positions. A circle of radius 12 pixels (9.′5) around each ghost is marked and not used when the images are co- added.

Next the images are approximately aligned by shifting and rotating to remove the positional dither. They are then aligned more exactly by finding the positions of all the intermediate brightness stars, those with central intensity between 10 times the sky foreground and a level of 14000 ADU, and then finding the shifts and rotation which minimize the differences of position between the stars on each image compared to the first one of the set.

The aligned images are then co-added after removal of cosmic ray events and other transients. As described above, this is done by first finding at each pixel position the median of the set of images, and the median of the absolute difference from this median. For small numbers of points, the mean can be significantly different from the median, so now the true mean at each pixel position is calculated, excluding those points whose difference from the median is more than 3.5 times the median absolute difference. Regions containing ghosts are also excluded when calculating the mean.

3.3. Continuum Subtraction

At this point we have co-added means of the images taken through the Hα and continuum filters, with transients and ghosts removed. Next the continuum image is aligned to the Hα image, using the same procedure as described above. Aperture photometry on the same intermediate brightness stars on each image establishes an intensity scale factor between the two mean images. The continuum image, multiplied by this scale factor, is then subtracted from the Hα image. The continuous airglow foreground and most stars are removed by this procedure, but the geocoronal Hα emission and residuals of the bright stars remain. These bright star residuals are probably due to slight differences of the point spread functions on the two images, small non- linearities of the CCD response, or saturation of the detector (for the very brightest stars). A sample of the continuum, Hα, and star-subtracted images for one field is shown in Figure **??**.

The image should in principle now contain only line emission, primarily Hα, both interstellar and geocoronal, and stellar Hα emission and absorption, as modified by the transmission function of the Hα filter. (There remains also some residual contamination by telluric OH lines—Section 2.2.) The basic transmission function is determined by dividing the Hα flat (produced by observing the lightbox illuminated by the hydrogen emission lamps) by the continuum flat (produced by observing the lightbox illuminated by the incandescent lamps), both with the Hα filter in place, and both normalized to the mean of the central 100 pixel $\times$

100 pixel area. In principle the Hα component of the original images should be corrected for this transmission factor before they are shifted and co-added, but it is difficult to separate accurately the line and continuum fractions of the image before the co-addition. Therefore we constructed an effective Hα transmission function by de-dithering and co-adding the original function in precisely the same way as was done for the original images obtained with the Hα filter. The star-subtracted image was then divided by this function to obtain a corrected image, with the transmission characteristics of the Hα filter removed.

3.4. Corrections

For many fields, this procedure produces a good image, planar except for real interstellar Hα features. For some fields, however, obvious instrumental effects remain. One of these manifests itself as an increase of brightness with radius, in shape like the inverse of the Hα filter transmission function (Figure **??**). This probably arises from imperfect subtraction of the continuum, perhaps due to the foreground brightness changing non-linearly with time. If some continuum radiation remains in the image, then division by the Hα filter transmission function will cause such an upturn near the edges. To correct for this phenomenon, we iteratively subtracted from the images showing this effect a constant divided by the Hα filter transmission function until we found the value which minimized the upturn near the edges.

Even with this effect removed, some images showed a residual pattern at low amplitude (a few rayleigh) of a circularly symmetric brightness, rising and then falling with radius. Such an effect could arise from one or more emission lines in the night sky spectrum shifting across the filter band with increasing angle of incidence. But the position and shape of the maximum does not seem to correspond with that expected for any known line. It could also be some artifact of the flat-fielding procedure. The cause of this effect is not understood.

We determined this function individually where we could, for those images which contained no bright interstellar Hα features, by finding the average of each image at constant radial distances from the center, after normalizing the image to have zero mean, and subtracting this circularly symmetric function from the image. For those fields, mainly at low galactic latitudes, where the genuine Hα features were too bright for this procedure to work, we merely subtracted the average of all the functions determined at high latitudes.

An example showing graphs of the average brightness as a function of radius for an original continuum-subtracted image and for the same image after these two stages of correction is shown in Figure **??**.

3.5. Smoothing

These procedures produced images which are fairly planar, but they do contain geocoronal Hα emission (and possibly some residual OH emission) as well as Hα emission from the interstellar medium. The geocoronal emission is variable in time and with position on the sky. We have assumed that it changes fairly slowly in both dimensions, and have modelled it as a plane with a certain level (which we call a piston), slope in declination (tip), and slope in right ascension (tilt). We determined these parameters (piston, tip, and tilt) for each image so that neighboring fields fit together into a smooth mosaic, as described in Section 5.

Finally, as mentioned above, the star-subtraction procedure does not work perfectly, so that the images contain some high spatial frequency residuals of imperfectly subtracted bright stars. We removed these as best we could, but with some loss of resolution, by applying a spatial median filter of width 5 pixels ($4'.0$) to the images. The smoothed image for the Orion region is shown in Figure **??**d.

3.6. Astrometry

By automated pattern-matching of stars in our images to those in the SAO catalog, we determine astrometric solutions for each mean Hα and mean continuum image. The solution, a gnomonic projection, is stored in the image header according to standard practice (Calabretta & Greisen 2000). Here we detail the method of solution and describe its accuracy. The method is similar to others that we might have used (e.g., Mink (1997)) if they had existed when we first needed them.

After each observation, the telescope control software annotates the image header with the celestial coordinates of the intended center of the image. From the image, our algorithm generates a list of stars' centroids and instrumental magnitudes. From the SAO catalog, our algorithm culls a list of J2000 positions and apparent visual magnitudes of stars within 9° of the intended center. The stars' celestial positions are converted to angles (ξ, η) of a gnomonic projection centered on the image's intended center (e.g., Marsden (1982)). The pattern-matching algorithm compares the list of instrumental centroids and magnitudes to the list of gnomonic angles (ξ, η) and SAO magnitudes. It uses Valdes' method of similar triangles (Valdes et al. 1995) as implemented by Richmond (1996) to determine a tentative match between the 50 brightest stars in one list and the 50 brightest stars in the other list. It then iteratively refines the solution by extending the star lists, typically to 200 stars in common. The custom keyword N_ASTROM in the image header logs the number of stars that contributed to the astrometric solution.

The instrumental positions match the catalog positions to 0.18 pixel ($8''$) r.m.s. if first-order plate equations are applied. The residuals of the first-order fit exhibit a third-order polynomial with maximum amplitude of ± 0.4 pixels ($\pm 0\farcm32$). Fitting with third-order polynomials reduces the r.m.s. of the residuals by a factor of two, but for simplicity we chose to retain only the first-order fit in the image header.

Astrometric solutions were computed separately for the co-added Hα and continuum images. Because the continuum image was shifted to match the Hα image prior to subtraction, the continuum-subtracted images and the smoothed images have the same astrometric solution as the Hα image.

4. Intensity Scale

To calibrate the intensity scale of our images, we compared aperture photometry of many compact (diameter $< 5''$) planetary nebulae (PNe) on our images with the spectrophotometric fluxes reported by Dopita & Hua (1997) (see Figure **??**). Dopita & Hua report fluxes for Hα (656.3 nm) and the forbidden line of [N II] at 658.34 nm. The latter spectral line and its companion at 654.81 nm contribute to the flux in our "Hα" images. The intensity of [N II] 654.81 nm is 1/3 that of [N II] 658.34 nm (Osterbrock 1989). The transmission of the "Hα" filter, at our 25 °C operating temperature and at normal incidence[2], is 39%, 78%, and 26% at 654.81 nm, 656.3 nm, and 658.34 nm respectively. By accounting for the expected relative contributions to the flux measured through our filter for each PN according to the fluxes given by Dopita & Hua, we determined the single scalar that best matched our instrumental fluxes (in analog to digital units, or ADU) to theirs (in ergs cm^{-2} sec^{-1}). We chose to use in the comparison group only those PNe that had an Hα flux larger than $10^{-11.25}$ ergs cm^{-2} sec^{-1}, because many of the fainter ones had large uncertainties in our aperture photometry. If the aperture photometry routine [APER in the IDL DAOPHOT package (Landsman 2001)] reported an error of less than 6% for any particular measurement, we replaced that error estimate with 6%; three such replacements occurred in each of the two groups (open or filled circles) plotted in Figure **??**. For those 18 PNe selected for the intensity calibration, the r.m.s. differences between our Hα fluxes, determined from continuum-subtracted images and corrected for [N II] emission, and the Hα fluxes of Dopita & Hua, is 8%. Because Dopita & Hua's spectrophotometry is accurate to better than 1%, we

[2]The filter's transmission at 654.81 nm increases with increasing angle of incidence, while at 658.34 nm the transmission decreases with increasing angle of incidence(Figure **??**). The net effect is that the intensity-weighted average transmission of the two [N II] lines is a weakly varying function of angle of incidence that we have not attempted to allow for in determining the overall intensity calibration.

consider the 8% r.m.s. scatter between our measurements and theirs as indicative of the limit of precision of fluxes of unresolved sources measured from our continuum-subtracted images. We attribute this 8% limit (1σ) on precision to uncorrected extinction (Section 2.5) and the undersampling of the optical system's point spread function by our pixels. The transmission of our "continuum" filter at the wavelength of the [SII] line at 673.1 nm is 16% at normal incidence, and as large as 70% at the corners of our images (2.2), but because our continuum images are exposed for 25% of the time of the Hα images, and because in all of these PNe the [S II] λ673.1 line is less than 10% the brightness of Hα, we have not corrected our fluxes for [SII] as we did for [N II]. As a worst-case example, a single measurement of a particular PN that happened to be near the corner of an image, the leakage of [S II] λ673.1 would amount to less than 2% of the Hα flux. In an image in which that same PN appears near the center, the effect would be less than 0.4%. Using the PNe calibration just described, and converting from flux to surface brightness units, we find that in a single pixel of our Hα images, 1 R $= 6.8 \pm 0.3$ ADU. This factor has been applied to all the continuum and smoothed images available for public use (Section 6.3); their intensities are expressed in units of decirayleighs (1 dR = 0.1 R).

As an independent check of the calibration using the 18 PNe described previously, we compared our measurement of the total Hα flux of the very bright Rosette nebula to the Hα flux measurement of Celnik (1983). Integrating the flux within a 1° radius circle, as Celnik did, and setting our image's zero point to agree with the dashed contours of Celnik's Figure 2, and correcting our measurements for [N II] leakage with the spectral line ratio measured for the Rosette, I(6583)/I(Hα) = 0.37 (Johnson (1953); position 58) we find 1 R $= 7.4 \pm 0.5$ ADU, where the uncertainty is set by the 7% uncertainty reported by Celnik for the integrated Hα flux. Because the PNe calibration is based upon many objects measured on many images rather than a single object (the Rosette) measured on a single image, the Rosette calibration is secondary to the PNe calibration that we actually applied, 1 R = 6.8 ± 0.3 ADU. The ratio of the two (7.4/6.8 = 1.09) indicates that our intensity calibration is consistent with others to approximately $\pm 9\%$. (See Section 6.2 for comparisons with other surveys.)

5. Removal of Geocoronal Emission

Each individual Hα image[3] has an unknown offset due primarily to geocoronal Hα emission, which is spatially and temporally variable. To account for variations in geocoronal emission, we have adopted a model in which the extra foreground emission is a 2-dimensional (2-D) plane, the three parameters of which we call "piston" for the mean value of the intensity of the foreground ($\bar{F}$) and "tip" and "tilt" (collectively ∇F) for the foreground's slopes. Thus, the galactic emission, I^g, that we seek can be determined from the emission that we observe, I^o, as follows:

$$I^g = I^o - (\bar{F} + \nabla F \cdot \vec{X}), \tag{8}$$

where $\vec{X}$ is a linear transform of the x- and y-coordinates of each pixel: $\vec{X} = [(x- < x >)/ < x >, (y- < y >)/ < y >]$.

The challenge is to find the specific $\bar{F}$ and ∇F for each individual image in a physically justified manner.

Our approach to this challenge extends the method of Regan & Gruendl (1995) in a few ways: 1) theirs solves for $\bar{F}$, while ours solves for $\bar{F}$ and ∇F; 2) theirs matches pixels in one image with pixels in an adjacent image using a simple shift in $\vec{X}$, while ours uses the astrometry stored in the FITS headers; 3) theirs uses a median of differences of matched pixels in each overlapping region, while ours fits a 2-D plane to those differences; 4) the overall zero-point(s) for the pistons (and tips and tilts in our case) are determined by different methods; 5) their algorithm for solving the system of equations is a simplex method; ours is a singular value decomposition. The large angular size of our images required us to implement item 1 because the foreground sky is not constant across an image, item 2 because of image distortion and rotation, especially near the celestial pole, and item 3 because according to our model the difference between two adjacent images is a 2-D plane whereas in their model the difference is a single scalar.

Our method of determining the specific $\bar{F}$ and ∇F for each individual image is best described by an example. Figure **??** shows four overlapping images. There are five pairs of overlapping images: images 1 and 2, 1 and 4, 2 and 3, 2 and 4, plus 3 and 4 overlap. We begin with the overlap between image 1 and 2. We subsample the "good" part of image 2 on a 20 pixel by 20 pixel grid and compute the position on the sky (α, δ) of each pixel from image 2's astrometric solution. For those (α, δ) we compute the (x,y) in image 1's astrometric frame in order to pair the pixels in image 2 with pixels in image 1 at the same

[3]Throughout this Section, "image" means an image that has been completely calibrated according to the description in the previous sections, unless specified otherwise.

(α, δ). Each such pair of pixels provides an equation such as

$$I_1^o - I_2^o = (I_1^g + \bar{F}_1 + \nabla F_1 \cdot \vec{X}_1) - (I_2^g + \bar{F}_2 + \nabla F_2 \cdot \vec{X}_2), \tag{9}$$

where the subscripts refer to the image (1 or 2) and the superscripts (o or g) refer to observed or galactic intensity. Because the galactic emission is constant with time, i.e., $I_1^g = I_2^g$, it cancels out in the difference and we have

$$I_1^o - I_2^o = (\bar{F}_1 + \nabla F_1 \cdot \vec{X}_1) - (\bar{F}_2 + \nabla F_2 \cdot \vec{X}_2). \tag{10}$$

In this equation we have observed I_1^o at location $\vec{X}_1$ of image 1 and have observed I_2^o at $\vec{X}_2$ of image 2. The unknown parameters for images 1 and 2 are $\bar{F}_1, \nabla F_1, \bar{F}_2$, and ∇F_2.

Likewise, each pixel in image 3 that overlaps image 2 provides an equation

$$I_2^o - I_3^o = (\bar{F}_2 + \nabla F_2 \cdot \vec{X}_2) - (\bar{F}_3 + \nabla F_3 \cdot \vec{X}_3). \tag{11}$$

and similarly for the three remaining overlapping image pairs.

We can define a matrix equation $\vec{b} = \mathbf{A} \cdot \vec{v}$ where vector $\vec{b}$ contains the intensity differences between all pixel pairs of image i and image j, i.e., $\vec{b} = \{I_i^o - I_j^o\}$; vector $\vec{v}$ contains the model parameters, i.e., $\vec{v} = \{\bar{F}_i, \nabla F_i\}$; and $\mathbf{A}$ describes the coupling of $\vec{b}$ and $\vec{v}$ by equations like those above. In the illustrated example, $\vec{v}$ would be 12 elements long (4 images and 3 parameters per image). Each pair of pixels from adjacent images adds an element to $\vec{b}$ and a row to $\mathbf{A}$.

We then solve $\vec{b} = \mathbf{A} \cdot \vec{v}$ for $\vec{v}$ by a standard method of linear algebra, singular value decomposition. However, even if we have more equations than unknowns, the equations are degenerate such that the overall piston, tip, and tilt are arbitrary. In many circumstances it may suffice to append three rows to $\mathbf{A}$ to force the mean values $< \bar{F}_i >$ and $< \nabla F_i >$ to zero. Another option is to refer the data to intensity values known by other means. In our case we get additional equations by comparing our data with WHAM data.

If all calibrations are done correctly, if we average our data over a 1°-diameter circle of sky and integrate WHAM's spectra over velocity while eliminating the geocoronal emission in the spectra, and if the contamination of our data by telluric OH emission is negligible, then our measurement of the galactic Hα intensity and WHAM's should be equal, i.e., $< I^g >= I_{WHAM}$. Three WHAM data points are shown in Figure **??** as circles. In our hypothetical example, we append to $\mathbf{A}$ equations like the following:

$$< I_3^o(c) > - I_{WHAM}(c) = (\bar{F}_3 + \nabla F_3 \cdot \vec{X}_3). \tag{12}$$

In this equation, which applies to point c in Figure **??**, $< I_3^o(c) >$ is the observed intensity of image 3 centered on point c and averaged over a 1° diameter circle that corresponds to the WHAM beam size; $I_{WHAM}(c)$ is the intensity at point c as measured by WHAM; and $\vec{X}_3$ is the location of point c in image 3's coordinate system. In principle, only three such fiducial points (e.g., points a, b, and c) are needed to constrain the overall piston, tip, and tilt. We append to **A** equations similar to the one above for image 2 and point a, image 3 and point b, and image 4 and point c, but not image 2 and point b because the circle around point b does not lie wholely within image 2's "good" region, making $< I_2^o(b) >$ inaccurate.

For small numbers of images, it is practical to simply use a very sparsely subsampled grid of pixels, and let every pair of pixels lengthen $\vec{b}$ by one element and **A** by one row. Because the time to solve the equation $\vec{b} = \mathbf{A} \cdot \vec{v}$ for $\vec{v}$ grows in proportion to the product of the number of pixel pairs times the square of the number of free parameters of the model (in our case, three times the number of images), a more efficient approach is required for large numbers of images. We chose to subsample our images, and then in each region of overlap, we inscribed a rectangle and within the rectangle we fit a 2-D plane to the differences in intensities of paired pixels. We then evaluated the plane at the corners of the rectangle and used those values as representative of all the paired-pixel differences and locations in the region of overlap. Choosing the rectangle's four corners of course over-determines the plane, but doing so is a simple and approximate method of representatively weighting the data as it would be if all pixels within the irregularly-shaped region of overlap were given equal weight. An iterative method is used to fit the plane robustly, i.e., such that outliers do not affect the solution.

Simulations in which a large image is carved into a set of overlapping images and then random pistons, tips, and tilts are added to those images, and subsequently solved for, show that our algorithm can recover the pistons, tips, and tilts very accurately and reliably under optimum conditions. In practice, with our actual Hα images, our experience with the algorithm has been much less satisfying.

With our Hα images, if we solve for $\bar{F}$ and ∇F simultaneously the solution tends to introduce large scale undulations in the mosaic of the (galactic) Hα sky. Wherever the solution is not tied to fiducial points, such as in the southern sky ($\delta < -30°$) where no WHAM data exists, the solution tends to be unreliable. Slightly different input parameters give rather different results, even physically impossible results, such as negative brightness in some regions. The solution tends to err in such a way that in extrapolating beyond the set of images containing WHAM fiducial points to those without any, erroneous gradients trade off with erroneous pistons, so that the solution is "smooth" from one image to another, but has the wrong overall "figure" or shape. We tested the reliability and accuracy by using a subset of the WHAM data to determine a solution and a different subset to compare with our data after the solution has been applied. For example, to test our algorithm's ability to extrapolate from the north to the south, i.e., from where there is WHAM data to where there is not, we included as input (cf. Equation 12) WHAM data with declination $\delta \geq -5°$, determined a solution, applied it to our images, and then compared our resulting Hα intensities with WHAM data in the region $-25° \leq \delta \leq -10°$. This empirical test convinced us that in order to prevent the solution from diverging in the southern sky where no WHAM data exists, i.e., $\delta < -30°$, we had to provide additional, artificial fiducial points in that region that would be treated the same as actual WHAM observations.

In order to create these artificial fiducial points, which are shown in Figure **??**, we fit a function of the form $C_1 + C_2/sin|b|$ to WHAM data with $-25° \leq \delta \leq +10°$ and $|b| > 30°$, but excluding the Orion/Eridanus region, $150° < l < 230°$. The parameters C_1 and C_2 were fit by eye in order to ignore the somewhat-brighter regions remaining within those limits of δ, b, and l. The function so selected,

$$I^g(model) = -0.75 + 1.0/sin|b| \text{ [rayleighs]}, \tag{13}$$

is plotted in Figure **??**. That the Hα sky is fainter at high latitudes than the extrapolation of a $csc|b|$ law determined at lower latitudes is believed to be due to the Local Bubble, plus a small, increasing contribution for dust-scattered Hα at the lower latitudes (Wood & Reynolds 1999). If we assign all of this effect to the Local Bubble, then the isotropic component in Equation 13, -0.75 R, corresponds to the emission missing from that part of the WIM that the Local Bubble has "carved out." For a mid-plane r.m.s. electron density $\sqrt{< n_e^2 >} = 0.084$ cm^{-3} (Reynolds 1991), the "missing" Hα intensity of 0.75 R requires a 240-pc path length of fully ionized gas at 8000 K. That length is approximately equal to the 200-pc radius of the Local Bubble as modeled by Wood & Reynolds (1999), so our paramter $C_1 = -0.75$ rayleigh is consistent with prior models for the local WIM.

In the end, we chose to include data from all 542 images to determine simultaneously the $\bar{F}$ and ∇F for each of the images. With 3166 pairs of overlapping images, and each region of overlap represented by 4 points as previously described, there were 12664 equations like Equation 10. We used 802 WHAM reference points spaced 4° in right ascension between $0^h \leq \alpha \leq 24^h$, and spaced 5° in declination between $-25° \leq \delta \leq +10°$. We did not use any WHAM-measured surface brightnesses less than zero (because those are probably erroneous) or larger than 30 R because we wanted to avoid bright regions for which multiplicative errors might affect our estimate of the additive terms. We also used 527 artificial points created as described previously (cf. Equation 13). The 802 WHAM fiducial points and 527 artificial fiducial points have 4803 separate measurements in our set of 542 images, resulting in 4803 equations like Equation 12. In order to give approximately equal weight to the two types of equations, i.e., those that compared overlapping images (Equation 10) and those that compared our data to WHAM data (Equation 12), we replicated the latter 4803 equations to produce 9606 such equations, or nearly as many as the 12664 equations of the other type. We then solved the equations for the 542 images' $\bar{F}$ and ∇F by singular value decomposition. We solved the equations twice; prior to the second iteration, we discarded 52 (0.4%) of the 12664 equations that were found to deviate by more than 10 times the average residual difference after applying the initial solution's $\bar{F}$ and ∇F. As expected, because only a very small fraction of the equations were excised, the second set differed only very slightly from the first set. The pistons, tips, and tilts determined in the second set were applied to the continuum-subtracted (and corrected) images and the smoothed images (Sections 3.3–3.5), and the latter were used to make the mosaic map mentioned in Section 6.1.

6. The Survey

6.1. Description and Sample Images

The survey consists of 268 fields covering the sky from $-90°$ to $+15°$ declination, with the same centers as those in the IRAS Sky Survey Atlas (ISSA)(Wheelock et al. 1994), plus, instead of ISSA region 001, three fields centered at $-87\overset{\circ}{.}5$ declination and 0, 8, and 16 hours right ascension to cover the polar region. In order to reduce the noise in mosaic maps and to allow confirmation of objects discovered at the faintest brightness levels, we repeated all fields with offsets of 5° in both coordinates. (The three polar fields were repeated at the same declination, $-87\overset{\circ}{.}5$, but displaced 4 hours in right ascension.)

The field centers are listed in Table 1.

Images of the individual fields are available from our web site (Section 6.3). Some examples of interesting fields are shown in Figure **??**, and a mosaic of the entire region of the sky included in the atlas is shown in Figure **??**.

All observations used in the survey were obtained in the period November 1997 to October 2000, a time of increasing solar activity.

6.2. Comparison with Other Surveys

6.2.1. VTSS, the Virginia Tech Spectral-Line Survey

The Virginia Tech Spectral-Line Survey (VTSS) is an imaging survey similar to the one described here but for the northern hemisphere (Dennison, Simonetti, & Topasna 1998). When the VTSS observations of the northern hemisphere are complete, combining them with our southern hemisphere data will provide an all-sky Hα mosaic with approximately $3'$ resolution. Comparison of VTSS data with our own shows they are very similar, but with some differences, as the remainder of this section describes.

The VTSS includes much of the Milky Way ($|b| \lessapprox 30°$) clearly visible ($\delta \gtrapprox -15°$) from the Martin Observatory in southwestern Virginia. The VTSS's cryogenically-cooled CCD camera has a 58-mm lens, 27 μm pixels, a scale of $1\farcm6$ pixel^{-1}, and covers a $13\fdg6 \times 13\fdg6$ field of view. The 1.75 nm bandwidth (FWHM) of the VTSS's Hα filter limits the usable field of view (cf. Equation 2) to a 10° diameter circle centered on the optical axis. As soon as they are processed to final form, individual images from the VTSS are posted on the VTSS web site (http://www.phys.vt.edu/˜halpha/).

In order to make the comparison, we selected four continuum-subtracted Hα images from the VTSS: Aql04, Aql12, Cnc02, and Ori11. [The first three letters of each image's name refer to the constellation (Aquila, Cancer, and Orion) and the number is simply a counter.] Each of the first three VTSS images is an average of six 360-second exposures, and the last image (Ori11) is an average of twelve 600-second exposures.

We mapped, pixel-by-pixel, all of our final smoothed images that overlapped each VTSS image onto that VTSS image. Because our pixel size is $0\farcm8$ and the VTSS images' pixel size is $1\farcm6$, each of our images has four pixels within the area of one VTSS pixel. Between seven and ten of our images overlap each VTSS image, but most of them do so only partially, such that typically two to four of our images cover a particular point on the sky. Thus, in mapping our images upon a VTSS image, we average between 8 and 16 pixels' data for each VTSS pixel. The resulting mosaic of our images, custom-made to match the pixel scale and orientation of the VTSS image, is then nearly ready to be compared with the VTSS image.

Because a constant has been subtracted from each VTSS image to force its median to be zero, we need to correct the zero-point of intensity scale of each VTSS image. Rather than calculate a simple offset, we fit an arbitrary 2-D plane of emission to the difference between the VTSS image and our custom-made mosaic. By subtracting that 2-D plane from the VTSS image, we effectively corrected the VTSS image for whatever geocoronal or telluric OH foreground emission might be included in it. (Our images have been corrected already for this emission as described in Section 5.)

At the top of Figure **??**, we show the VTSS image Aql04 and our custom-made mosaic, for side-by-side visual comparison.[4] Notably, the structure of the diffuse emission is nearly

[4]Actually we have also corrected the grey scale of the VTSS image Aql04 by dividing it by 0.80, a factor that will be explained shortly.

identical, as it should be, because both of us are measuring the Hα emission. The VTSS image has more noticeable residuals around stars, but aside from that the two images are nearly identical. The width of the point spread function, measured from the same few unresolved emission knots, is ~ 2 pixels ($3\farcm2$) FWHM in either image. In the VTSS images, this FWHM represents an intrinsic resolution limit, while in our case it represents a kind of effective width of the native resolution of our images and the $4' \times 4'$ kernel of the median filtering of our images, combined with the binning and averaging of multiple images that make up each custom-made mosaic.

Also in Figure **??**, in the lower left panel, we show a pixel-by-pixel comparison of the VTSS image Aql04 and our mosaic image, after each has been convolved with a 5×5 pixel ($8' \times 8'$) kernel. The convolution serves only to reduce noise and to reduce effects of slightly dissimilar point spread functions. Rather than plot *every* pixel, which would make the density of points in the plot too high, we randomly selected 1% of the pixels across the image for the plot. From this plot, and especially the one next to it, from the Ori11 region, we determine that the intensity calibration of our data and the VTSS data are not the same. For an object within the Ori11 region, the surface brightness measured from a VTSS image will be 80% that measured from our images. For the Aql04 region the measured value is 85%, but with greater uncertainty due to the smaller dynamic range of surface brightness in Aql04 compared to Ori11. For the other two images, Aql12 and Cnc02, the Hα emission is too faint for the intensity ratio to be determined accurately. For display purposes, we have corrected the VTSS image Aql04 in Figure **??** by dividing it by 0.80, but we have not attempted to determine the cause of this effect or whether it affects other VTSS images or perhaps only these two images that we have examined.

In order to compare the sensitivity of our survey to that of the VTSS, we further processed the images of the two regions Aql12 and Cnc02, which have some faint emission in them, by median filtering each with a $0\fdg4 \times 0\fdg4$ kernel and subtracting the result from each image in order to create residual images. The purpose of creating residual images is to prevent genuine emission from affecting our measurement of the noise in the image. The r.m.s. surface brightness in those residual images were 0.23 R and 0.15 R for VTSS images Aql12 and Cnc02, respectively[5], and 0.22 R and 0.22 R respectively for their associated custom-made mosaics from our data. In determining the r.m.s., we used only the cores of the distributions, not the wings that are created by the residuals around stars. Thus, except for the possible difference in overall intensity calibration, when convolved to a similar resolution, our data and the VTSS data give similar results in those regions of sky in which

[5]If the factor of 0.80 determined from the Ori11 field should apply to the Aql12 and Cnc02, then the values 0.23 R and 0.15 R should be adjusted to 0.29 R and 0.19 R, respectively.

they overlap (i.e., for $-15^\circ \lessapprox \delta \lessapprox +15^\circ$, and $|b| \lessapprox 30^\circ$).

6.2.2. WHAM, the Wisconsin H-Alpha Mapper survey

As noted in Section 1, the WHAM survey is a velocity-resolved survey of Hα emission over 3/4 of the entire sky ($\delta \gtrapprox -30^\circ$). The WHAM survey consists of more than 37,000 individual spectra, each with velocity resolution of 12 km s^{-1} over a 200 km s^{-1} (0.44 nm) spectral window. Each velocity-integrated spectrum has a 3σ sensitivity of 0.15 R over its 1° diameter beam. Geocoronal Hα emission is separated from Galactic Hα emission spectrally in the WHAM data. Because of the WHAM survey's sensitivity and accuracy, it is an ideal data set to compare our own to, after appropriately integrating the WHAM spectra and smoothing our data to match WHAM's 1° angular resolution.

Figure **??** compares WHAM data with our own. In Figure **??**, the WHAM values are velocity-integrated and have had geocoronal emission removed (Reynolds 2001), while this work's values are the average within the 1° diameter beam of WHAM of our final smoothed images after removal of geocoronal emission as described in Section 5. The locations on the sky of the 834 points plotted in Figure **??** are shifted 2° in right ascension with respect to the locations of the points used to fit and remove the geocoronal emission, in order to assure that the set of points used for the comparison contains none of the points used for the fitting.

The r.m.s. of the residuals of points with WHAM-measured surface brightness less than 2 R is 0.4 R. Because the WHAM sensitivity is 0.05 R (1σ), the 0.4 R r.m.s. difference between WHAM's values and our own is almost entirely due to our data's noise and is an empirical limit of the sensitivity of our data after convolution with a 1°-diameter beam. For faint sources, the dominant errors are additive, but for bright sources, multiplicative errors could be more important than additive ones. In fitting and removing foreground emissions (Section 5), we specifically excluded regions brighter than 30 R so that any multiplicative errors that might exist would not affect the fitting too badly. Consequently, for a fair comparison of our intensity scale to WHAM's, we should include only regions much brighter than 30 R in order to reduce the effect of the additive offsets determined by the fitting procedure. Generally, bright regions are better than faint regions for comparisons of two independent scalings of intensity. For the 15 points in Figure **??** with WHAM-measured surface brightness greater than 60 R, the ratio of our values to WHAM's has a mean of 1.00 and a 1σ dispersion of 0.13, i.e., our intensity scale matches WHAM's.

Ten points in the log-log (top) plot of Figure **??**, i.e., 1.2% of the total, are off-scale in the linear-log (bottom) plot; some of these outliers are caused by imprecise continuum-subtraction or bleed trails near bright stars, some represent small fractions of very bright intensities, and the remainder occur at regions with large variation in surface brightness across the 1° diameter WHAM beam and may be caused by the inaccuracy in our modeling it as a uniform circular disk even though it is slightly tapered near its edge.

The WHAM survey is more sensitive than ours, and because of the spectral information it contains, the foreground emission can be removed, providing absolute intensities, whereas we must resort to the method of fitting neighboring fields (Section 5) to put all of our images on the same intensity scale. On the other hand, our survey has greater angular resolution, which is important in the study of structure at small angular scales, such as in filamentary nebulae. To illustrate this point, in Figure **??** we show the Orion/Eridanus region as observed in both surveys.

6.2.3. The AAO/UKSchmidt Survey and the Marseille Observatory Deep Hα Survey

At the other end of the angular resolution scale are the photographic survey of the southern Galactic plane with the UK Schmidt Telescope of the Anglo- Australian Observatory (Parker & Phillipps 1998), and the deep Hα survey by the Marseille Observatory group with a scanning Fabry-Perot interferometer located at the European Southern Observatory in Chile (Russeil et al. 1998; Le Coarer et al. 1992). The former will provide images of $1''$ resolution over a $5\overset{\circ}{.}5$ field at a sensitivity of 5-10 R, but will be limited to the Galactic plane ($|b| < 10^\circ$). The latter has lower resolution ($9''$ pixels) and a smaller field of view ($0\overset{\circ}{.}6 \times 0\overset{\circ}{.}6$) but higher sensitivity (0.2 R) and of course gives velocity information lacking in an imaging survey. But it covers a very limited region of the Galactic plane ($234^\circ < l < 355^\circ$ and $-2^\circ < b < +2^\circ$). Figure 6.2.3 compares one of our images with a corresponding field from the AAO/UKST survey and one of the fields from the Marseille survey, both of the latter taken from Georgelin et al. (2000) (Figs. 1 and 6).

6.3. Access to the Survey Data

Images of individual fields in the survey may be examined on the web at http://amundsen.swarthmore.edu/SHASSA/ or http://www.lco.org/SHASSA/. Four images, similar to those shown in Figure **??**, are available for each location: Hα, continuum, continuum-subtracted, and smoothed (see Section 3 for a description of the processing involved in generating these image types). Individual images in FITS format may be downloaded via the above web page. Each full image file contains about 4 Mbytes, but compressed versions (in gzip format) are also available, averaging about 1 Mbyte each.

Those who wish to download a large number of images may find it more convenient to do so via the anonymous ftp server amundsen.swarthmore.edu/SHASSA/ or the alternative server ftp.lco.org/SHASSA/.

All of the survey images can also be obtained (in compressed form) as a set of three CD-ROMs. Contact Wayne Rosing (wrosing@lco.org) for details.

Those who use the survey images in a publication or publish research based on the survey images should include an acknowledgement to the "Southern H-Alpha Sky Survey Atlas, which was produced with support from the National Science Foundation" and make reference to this paper.

Reminder: Several factors may affect the photometric accuracy of the images in this atlas:

a) The removal of the geocoronal foreground emission (Section 5) is intended to offset each image so as to make them all consistent with sparsely-sampled WHAM data north of declination -30°. The accuracy of that process is discussed in Section 6.2.2 and displayed in Figure 13. South of declination -30°, the "background" intensity of each image is unverified and for some applications should be treated as a free parameter.

b) [NII] emission may contribute significantly to the "Hα" brightness and [SII] emission may distort the "continuum" brightness of some astronomical objects (Sections 2.2 and 4).

c) Telluric OH emission may contaminate both the Hα and continuum images (Sections 2.2, 3.3, and 3.4).

d) Corrections for other instrumental effects (Sections 3.1 and 3.4) may distort the relative brightness across some objects.

Users are advised to consider carefully how the reduction procedures described in this paper may affect their particular photometric applications.

6.4. Examples of Scientific Uses of the Survey

We have purposely excluded new scientific analysis from this paper. However, papers already published illustrate some of the scientific applications for which the type of data in this survey is appropriate.

First, the large size of the images ($13° \times 13°$) allows objects, such as the Large Magellanic

Cloud, to be seen in their entirety without the need for piecing together a mosaic (Gaustad, Rosing, McCullough, & Van Buren 1999).

Second, objects of low surface brightness but large angular size will be found here which have been missed in other studies. Two examples are the shell around the planetary nebula Abell 36 (McCullough et al. 2001a) and the 20°-diameter filamentary bubble centered on $(l, b) = (275°, 19°)$ (McCullough et al. 2001b) visible to the upper-left of the Gum nebula in Figure **??**.

Third, previous studies which were mainly qualitative can now be made more quantitative. For example, Hall (1999) calibrated the Sharpless brightness classes of diffuse nebulae on an absolute scale of rayleighs. [Hall also discovered faint outer extensions of several planetary nebulae with radii many times the radii listed in the Catalog of Galactic Planetary Nebulae (Acker et al. 1992).]

Fourth, the correlation of Hα emission with dust emission can be very informative. Dust clouds, bright at 100μm, often show a "silver lining" of Hα emission on the side facing strong ionizing flux coming from the UV-emitting stars in the Galactic plane (McCullough et al. (1999), Figure 7). In another example (Jenkins et al. 2000) a comparison of 100μm and Hα emission helped delineate the three-dimensional structure of the complex region near the Orion Belt star ζ Ori.

Finally, our survey has proved useful in setting limits on Galactic emission which might contaminate the DASI measurements of the cosmic microwave background (Halverson et al. 2001).

We expect that many other applications will be found for the images in this atlas.

7. Summary

In this paper, and on the accompanying web sites (http://amundsen.swarthmore.edu/SHASSA/ or http://www.lco.org/SHASSA/), we present a digital atlas of the southern sky ($\delta = +15°$ to $-90°$) as seen at 656.3 nm, the Hα emission line of hydrogen. The atlas consists of 542 fields, each field covering a $13° \times 13°$ region of the sky. The basic angular resolution is $0\farcm8$ pixel^{-1}. Smoothing to a resolution of $4\farcm0$ allows features as faint as 0.5 rayleigh to be seen.

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REFERENCES

Acker, A., Marcout, J., Ochsenbein, F., Stenholm, B., & Tylenda, R. 1992, Strasbourg - ESO Catalogue of Galactic Planetary Nebulae (Garching: European Southern Observatory)

Barnard, E. E. 1927, A Photographic Atlas of Selected Regions of the Milky Way (Washington DC: Carnegie Institution of Washington)

Broadfoot, A.L., & Kendall, K.R. 1968, J. Geophys. Res, 73, 426

Calabretta, M. & Greisen, E. W. 2000, in Astronomical Data Analysis Software and Systems IX, (Astronomical Society of the Pacific Conference Series, San Francisco), 216, 571

Celnik, W. E. 1983, A&AS, 53, 403

Chromey, F.R., & Hasselbacher, D. 1996, PASP, 108, 944

Dennison, B., Simonetti, J. H., & Topasna, G. A. 1998, Pub. Astron. Soc. Australia, 15, 147

Dopita, M. A. & Hua, C. T. 1997, ApJS, 108, 515

Gaustad, J. E., Rosing, W., McCullough, P. R., & Van Buren, D. 1999, IAU Symp. 190: New Views of the Magellanic Clouds, 190, 99

Gaustad, J. E., McCullough, P. R. & Van Buren, D. 1996, PASP, 108, 351

Georgelin, Y. M., Russeil, D., Amram, P., Georgelin, Y. P., Marcelin, M., Parker, Q. A., & Viale, A. 2000, A&A, 357, 308

Haffner, L. M., Reynolds, R. J. & Tufte, S. L. 1999, ApJ, 523, 223

Haffner, L. M. 2001, private communication

Haffner, L. M. et al. 2001, in preparation

Haffner, L. M. et al. 2001, http://www.astro.wisc.edu/wham/

Hall, K.J. 1999, Senior Thesis (Swarthmore PA: Swarthmore College, Dept. of Phys. & Astron.)

Halverson, N. W., Leitch, E. M., Pryke, C., Kovac, J., Carlstrom, J. E., Holzapfel, W. L., Dragovan, M., Cartwright, J. K.,Mason, B. S., Padin, S., Pearson, T. J., Shepherd, M. C., & Readhead, A. C. S. 2001, astro-ph/0104489, submitted to ApJ

Hamuy, M., Walker, A. R., Suntzeff, N. B., Gigoux, P., Heathcote, S. R., & Phillips, M. M. 1992, PASP, 104, 533

Hamuy, M., Suntzeff, N. B., Heathcote, S. R., Walker, A. R., Gigoux, P., & Phillips, M. M. 1994, PASP, 106, 566

Hewish, A., Bell, S. J., Pilkington, J. D., Scott, P. F., and Co11ings, R. A. 1968, Nature, 217, 709

Jenkins, E. B., Woźniak, P. R., Sofia, U. J., Sonneborn, G., & Tripp, T. M. 2000, ApJ, 538, 275

Johnson, H. M. 1953, ApJ, 118, 370

Landsman, W. 2001, http://idlastro.gsfc.nasa.gov/

Le Coarer, E., Amram, P., Boulesteix, J., Georgelin, Y. M., Georgelin, Y. P., Marcelin, M., Joulie, P., & Urios, J. 1992, A&A, 257, 389

Marsden, B. G. 1982, S&T, 64, 284

McCullough, P. R., Bender, C, Gaustad, J. E., Rosing, W., & Van Buren, D. 2001a, ApJ, 121, 1578

McCullough, P.R., Gaustad, J.E., Rosing, W. & Van Buren, D. 1999, in the Sloan Summit on Microwave Foregrounds, (Astronomical Society of the Pacific Conference Series, San Francisco), 181, 253

McCullough, P. R., Gaustad, J. E., Rosing, W. & Van Buren, D. 2001b, in Tetons 4: Galactic Structure, Stars and the Interstellar Medium, (Astronomical Society of the Pacific Conference Series, San Francisco), 231, in press

McCullough, P. R., Reach, W. T., and Treffers, R. R. 1990, BAAS, 22, 750

Mink, D. J. 1997, ASP Conf. Ser. 125: Astronomical Data Analysis Software and Systems VI, 6, 249

Netterfield, C.B., Jarosik, N., Page, L., Wilkinson, D., and Wo11ack, E. 1995, ApJ, 445, 69

Nossal, S., Reynolds, R. J., Roesler, F. L., Scherb, F., & Harlander, J. 1993, J. Geophys. Res., 98, 3669

Osterbrock, D. E. 1989, Astrophysics of Gaseous Nebulae and Active Galactic Nuclei (Mill Valley, CA: University Science Books)

Osterbrock, D. E. & Martel, A. 1992, PASP, 104, 76

Osterbrock, D. E., Fulbright, J. P., Martel, A. R., Keane, M. J., Trager, S. C., & Basri, G. 1996, PASP, 108, 277

Parker, Q. A. & Phillipps, S. 1998, Pub. Astron. Soc. Australia, 15, 28

Parker, R. A. R., Gull, T. R., and Kirschner, R. P. 1979, An Emission-Line Survey of the Milky Way, NASA SP- 434, (Washington DC: NASA)

Regan, M. W. & Gruendl, R. A. 1995, in Astronomical Data Analysis Software and Systems IV, (Astronomical Society of the Pacific Conference Series, San Francisco), 77, 335

Reynolds, R. J., Scherb, F., & Roesler, F. L. 1973, ApJ, 185, 869

Reynolds, R. J. 1991, ApJ, 372, L17

Reynolds, R. J., Tufte, S. L., Haffner, L. M., Jaehnig, K., & Percival, J. W. 1998, Pub. Astron. Soc. Australia, 15, 14

Reynolds, R. J. 2001, private communication

Richmond, M. W. 1996, private communication (source code and documentation are available at http://freshmeat.net/projects/match/)

Russeil, D., Georgelin, Y. M., Amram, P., Georgelin, Y. P., Laval, A., & Marcelin, M. 1998, Pub. Astron. Soc. Australia, 15, 9

Seife, C. 2001, Science, 292, 823

Sivan, J. P. 1974, A&ASuppl., 16, 163

Smith, W. J. 1990, Modern Optical Engineering (New York: McGraw-Hill), p. 195

Stetson, P. B. 1987, PASP, 99, 191

Stone, R. P. S. & Baldwin, J. A. 1983, MNRAS, 204, 347

Valdes, F. G., Campusano, L. E., Velasquez, J. D., & Stetson, P. B. 1995, PASP, 107, 1119

Valls-Gabaud, D. 1998, Pub. Astron. Soc. Australia, 15, 111

Wheelock, S. L. et al. 1994, IRAS Sky Survey Atlas: Explanatory Supplement, JPL Publication 94-11, (Pasadena:JPL), p. A-1

Wood, K. & Reynolds, R. J. 1999, ApJ, 525, 799

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Table 1. Survey Field Centers[a]

Field	RA(1950)	Dec(1950)	RA(2000)	Dec(2000)	Long.	Lat.
002	00^h00^m	-80°00′	00^h03^m	-79°43′	305 .°6	-37 .°1
003	03^h00^m	-80°00′	02^h58^m	-79°48′	296 .°4	-35 .°7
004	06^h00^m	-80°00′	05^h56^m	-79°60′	291 .°8	-29 .°1
005	09^h00^m	-80°00′	08^h58^m	-80°12′	294 .°0	-21 .°7
006	12^h00^m	-80°00′	12^h03^m	-80°17′	300 .°8	-17 .°6
007	15^h00^m	-80°00′	15^h07^m	-80°12′	308 .°7	-18 .°9
008	18^h00^m	-80°00′	18^h09^m	-79°60′	313 .°8	-24 .°9
009	21^h00^m	-80°00′	21^h07^m	-79°48′	313 .°0	-32 .°5
010	00^h00^m	-70°00′	00^h03^m	-69°43′	309 .°1	-46 .°8
011	01^h44^m	-70°00′	01^h45^m	-69°45′	296 .°2	-46 .°7
012	03^h28^m	-70°00′	03^h28^m	-69°50′	286 .°0	-41 .°8
013	05^h12^m	-70°00′	05^h12^m	-69°57′	280 .°9	-33 .°9
014	06^h56^m	-70°00′	06^h56^m	-70°04′	280 .°8	-25 .°0
015	08^h40^m	-70°00′	08^h40^m	-70°11′	284 .°6	-16 .°9
016	10^h24^m	-70°00′	10^h25^m	-70°15′	291 .°1	-10 .°8
017	12^h08^m	-70°00′	12^h11^m	-70°17′	299 .°5	-7 .°7
018	13^h52^m	-70°00′	13^h56^m	-70°15′	308 .°4	-8 .°1
019	15^h36^m	-70°00′	15^h41^m	-70°10′	316 .°5	-11 .°9
020	17^h20^m	-70°00′	17^h26^m	-70°03′	322 .°5	-18 .°5
021	19^h04^m	-70°00′	19^h09^m	-69°55′	325 .°5	-26 .°9
022	20^h48^m	-70°00′	20^h53^m	-69°49′	324 .°4	-35 .°7
...	...	...	...	...	...	...

[a]Table 1 is published in its entirety in the electronic edition of PASP, and on the web sites http://amundsen.swarthmore.edu/SHASSA/ and http://www.lco.org/SHASSA/. A portion is shown here for guidance regarding its form and content.

FIGURE CAPTIONS

Figure 1—Transmission of the Hα and Continuum filters. The positions of interstellar emission lines and atmospheric OH emission lines are also shown.

Figure 2—Transmission of Hα light by the Hα Filter as a Function of Angle of Incidence.

The edges of our images are $\approx 6\overset{\circ}{.}6$ from the center, and the corners are $\approx 9\overset{\circ}{.}3$ from the center.

Figure 3—Average brightness deviation from the mean as a function of radius for continuum images with $|b| > 40°$. The vertical bars show the range of this function ($1\ \sigma$) for individual images.

Figure 4—Continuum, Hα, continuum-subtracted, and smoothed images of a region in Orion (counterclockwise from upper right).

Figure 5—Brightness as a function of radius for a typical continuum-subtracted image before correction and after two stages of correction.

Figure 6—Comparison of fluxes of compact planetary nebulae measured by us to fluxes reported by Dopita & Hua (1997). Our fluxes have been corrected for the two [N II] emission lines adjacent to Hα (see Section 4). The PNe represented by the solid circles were used to determine the overall gain calibration of our images (i.e., the number of ADUs per unit Hα flux), thus the mean difference between the fluxes in "this work" and those of Dopita & Hua is zero by definition of the gain factor: 6.8 ± 0.3 ADU corresponds to 1 rayleigh of Hα emission in 1 pixel. Fainter PNe (which were not used) are shown as open circles. The logarithms are base 10, and the units of the fluxes are ergs cm^{-2} sec^{-1}.

Figure 7—This hypothetical example of four overlapping images is used to explain the mosaicing method in Section 5. Each image is numbered and outlined by a bold solid line. A thin solid line outlines the "good" region of each image, shown as solid white; the grey region between the thin solid line and the bold solid line indicates the part of each image that is flagged as "bad" due to edge effects. Each region of overlap between a pair of "good" regions is indicated by an inscribed dashed rectangle. Circles indicate locations and sizes of regions observed by the 1° diameter beam of WHAM. Data within either the dashed rectangles and/or the circles contribute to determining each image's three free parameters, piston, tip, and tilt ($\bar{F}$ and ∇F).

Figure 8—Locations of WHAM surface brightness data are plotted on this Hammer-Aitoff projection as plus signs (+); these correspond approximately to 4° spacing in right ascension and 5° spacings in declination from -25° to +10°. Those WHAM points used to

determine the parameters of the fit in Equation 13 are enclosed in squares. The dots ($\cdot$) are spaced 4° in right ascension and 5° in declination from −85° to −35°, and with Galactic latitude $b < -20°$, but excluding regions near the LMC, SMC, and extended parts of the Gum nebula. Equation 13 is evaluated at the locations indicated by dots in order to constrain the fit for each individual image's piston, tip, and tilt in the southern sky as described in Section 5.

Figure 9—Equation 13 is plotted here as a solid line and is a fit to the subset of WHAM data defined in the previous Figure (the plus signs enclosed by squares). The data plotted here are from WHAM (Reynolds 2001).

Figure 10—Some interesting fields from the atlas: 108— l = 265°.3 , b = +19°.5, filaments in Antlia; 204— l = 190°.3 , b = −36°.7, part of the Eridanus Filament; 640— l = 255°.5 , b = +18°.5, a bright rim in Pyxis; 576— l = 261°.5 , b = −5°.5, part of the Gum Nebula and the Vela SNR; 150— l = 353°.5 , b = +22°.7, δ Sco; 187— l = 7°.3 , b = +22°.7, ζ Oph.

Figure 11—Hammer-Aitoff projection in Galactic coordinates of our continuum-subtracted Hα data.

Figure 12—Comparison of our continuum-subtracted Hα images to those of the VTSS survey shows them to be similar with a few differences (see Section 6.2 for details not in this caption). Our data (left image above), rendered to match one of the VTSS images (right image above), illustrates the comparison. The VTSS image, Aql04, 10° in diameter, centered on $19^h08^m\ +5°$ [2000], with North up and East to the left, was selected at random for the comparison, and from it an arbitrary 2-D plane of emission was subtracted in order to minimize the residuals between it and the image rendered from our data. The lower-left plot shows a pixel-by-pixel comparison of the data from those two images after convolution with a 5×5 pixel ($8' \times 8'$) kernel. If the intensity calibration of our data and the VTSS data were the same, the data would scatter about the diagonal solid line. The dashed line is a first-order fit (with zero intercept) to the data with slope 0.85. A similar plot made for the VTSS region Ori11, centered on $5^h24^m\ -9°$ [2000], is shown at lower-right. It has a large enough dynamic range of surface brightness to allow a good comparison of the VTSS intensity calibration with our own. The slope of the dashed line in the lower-right plot is 0.80.

Figure 13—The Hα surface brightness measured by WHAM and by this work are compared. This work's values are the average of our data within the 1°-diameter WHAM beam. In the top plot, the diagonal line indicates equality of the two surface brightness measurements and the two additional lines are Y = (1 ± 0.1)X $\pm$ 0.4 R, where X is the abscissa and Y is the ordinate of the plot. The bottom plot shows the same data as the top plot, but

in the form of residuals (our values minus WHAM's) compared to WHAM's values; in the bottom plot, the two curved lines are $Y = \pm(0.8 + 0.1X)$ R. The r.m.s. of the residuals of points with WHAM-measured surface brightness less than 2 R is 0.4 R.

Figure 14—Our continuum-subtracted Hα data (upper image) and the WHAM survey data (lower image) of the same region, Orion/Eridanus, illustrate the effect of improved angular resolution in filamentary regions. The upper image has $2'$ resolution; the lower image has $60'$ resolution and has been interpolated between WHAM beams (data provided by Haffner (2001)).

Figure 15—Our field 033 (top), compared to field HA176 of the AAO/UKST survey (left) and the region around Gum 37 from the Marseille Observatory survey (right). The second image is scanned from Georgelin et al. (2000) and does not represent the full image quality of the AAO/UKST survey.

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This figure "fg14b.png" is available in "png" format from:

http://arXiv.org/ps/astro-ph/0108518v1