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Multiscale Structure in Dust Reflection and Cold H I

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Abstract. I present 2-D angular power spectra of cold H I emission and optical dust reflection tracing the H I in the Pleiades reflection nebula. This analysis reveals a uniform power-law slope of −2.8 over 5 orders of magnitude in scale, from tens of parsecs down to tens of astronomical units.

1. Introduction

Multiscale structure in the neutral atomic ISM is well known (e.g., Green 1993; Deshpande et al. 2000; Dickey et al. 2001). A quantitative examination of this structure over a wide range of scales may help us understand the physical causes (e.g. turbulent cascades), especially if the smaller scales can be probed. Such an examination is usually difficult with H I 21cm line observations, due to sightline confusion and sensitivity limits at high resolution. However, H I and dust should be well mixed in cold gas, so dust may trace H I structure at finer scales. Power-spectrum studies of dust infrared emission show power-law behavior similar to H I emission (e.g., Gautier et al. 1992), and one study of optical dust reflection in cirrus does as well (Guhathakurta & Cutri 1994).

Here I present optical and H I maps of the ISM associated with the Pleiades, where dust grains in a passing cloud are illuminated as a reflection nebula (Gordon & Arny 1984; White 1984; Breger 1987). Since the cluster is nearby ($\sim$ 130 pc; Percival et al. 2005) and there is minimal dust in front of the nebula (Černis 1987), optical features are easily related to specific spatial scales. The nebula's rich optical structure is illustrated in **Figures 1 and 2**. H I maps must be interpreted with more caution, since some emission may lie in the background; however, the emission shown in **Figure 3** has the same velocity as interstellar absorption associated with the nebula and matches the dust distribution in morphology.

2. Analysis

Each image was run through a 2-D Fast Fourier Transform (FFT) algorithm (Press et al. 1988), and a map of the FFT modulus was computed as the quadrature sum of the real and imaginary transform components. The modulus values were then binned by "radial frequency" $f_r \equiv \sqrt{{f_x}^2 + {f_y}^2}$, and the 2-D angular power spectrum $P(f_r)$ was constructed as the square of the median modulus in each f_r bin. The median statistic is robust against most artifacts that arise from "wraparound discontinuities" between the right and left or top and bottom

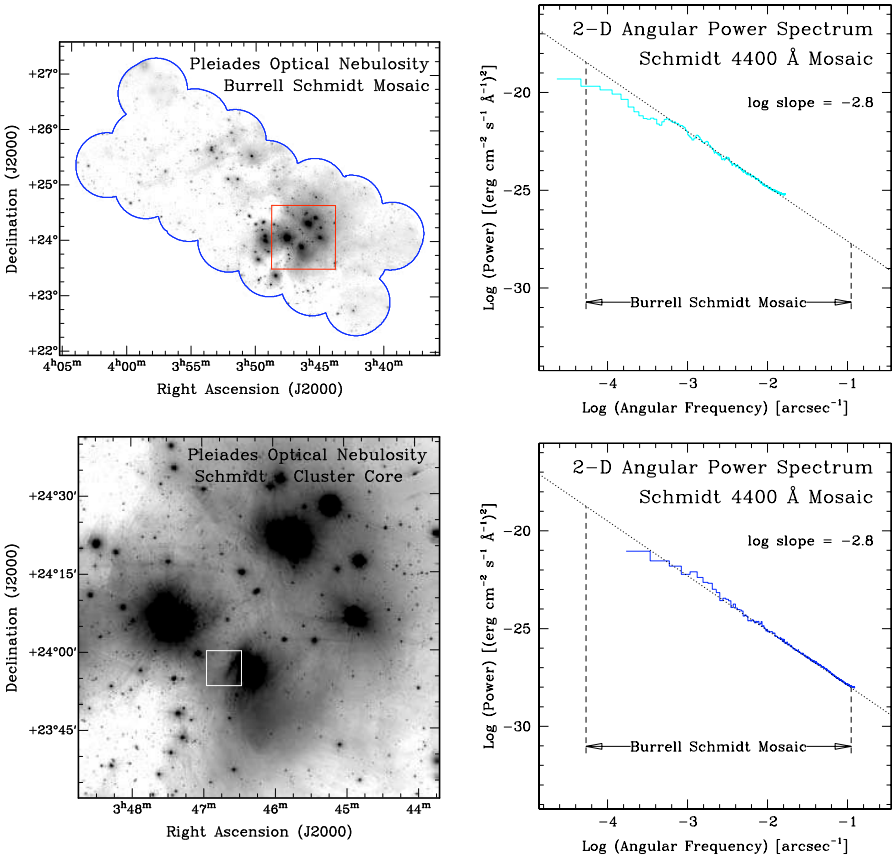

Figure 1. Pleiades optical nebula, negative logarithmic intensity scale. Top left: 40-field mosaic from the 0.6m Burrell Schmidt telescope (Gibson & Nordsieck 2003a). The boxed area is shown in the lower panel. Bottom left: nebular core in the same mosaic. The boxed area is shown in Figure 2. Right panels: 2-D angular power spectra derived from the images at the left.

image edges. However, the 2 or 3 lowest-frequency bins may still have excess power in some cases, particularly for the WIYN data. Image apodization alleviated this problem for the H I maps but did not help with the WIYN data; the Schmidt and HST images produced minimal edge artifacts. Stars were also removed from the WIYN image prior to the FFT, so the power spectrum is quite clean aside from edge effects. No significant stars were present in the HST image. Stars were not removed from the Schmidt mosaic, because the total map flux is dominated by the nebulosity near the brightest stars; however all saturated pixels were replaced by neighbor interpolation.

The power spectra are shown individually in **Figures 1 - 3** and together as a composite spectrum in **Figure 4**. Angular frequency is measured in cycles per arcsecond. The dashed lines indicate valid ranges of measurement, particularly where the resolution limits of different data sets occur; near the resolution frequency, photon noise flattens the WIYN and HST spectra, and H I power

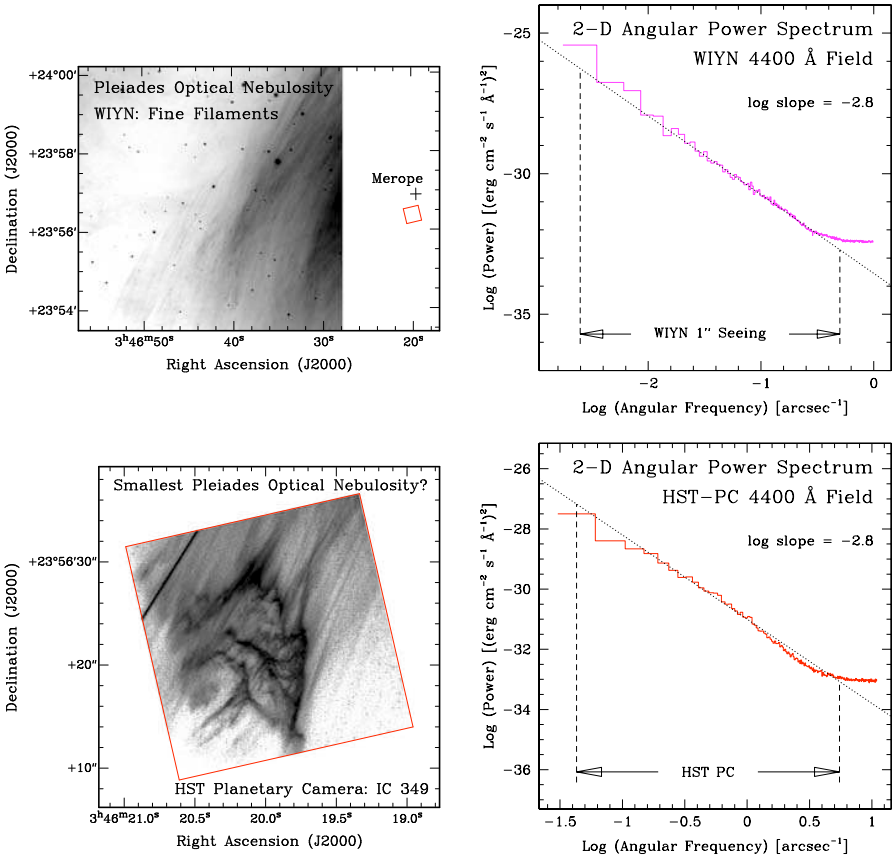

Figure 2. Pleiades optical nebula, negative logarithmic intensity scale. *Top left:* Wisconsin-Indiana-Yale-NOAO (WIYN) 3.5m image of nebular fine structure east of the 4th-magnitude star Merope, extended to indicate the position of the star and of the panel below. Image courtesy of C. J. Conselice and J. S. Gallagher. *Bottom left: Hubble Space Telescope* Planetary Camera (HST-PC) image of Barnard's Merope Nebula, IC 349 (Herbig & Simon 2001), 30″ south of Merope. Image courtesy of T. Simon. *Right panels:* 2-D angular power spectra derived from the images at left.

drops precipitously. Over 62% of the large-scale H I map is Dwingeloo data, so the 1° LAB Nyquist limit sets the resolution frequency for that spectrum.

3. Discussion

All power spectra in **Figures 1 - 4** are plotted against a power law with the same slope of −2.8, which was adopted from visual inspection. Within the dashed lines, most spectra are remarkably consistent with this power law. This includes the Schmidt spectra at scales $\lesssim 1000''$ ($\log f_r \gtrsim -3$), despite the presence of stars in the image. The consistency between the WIYN and Schmidt spectra supports both being dominated by nebulosity. At scales $\gtrsim 1000''$, the

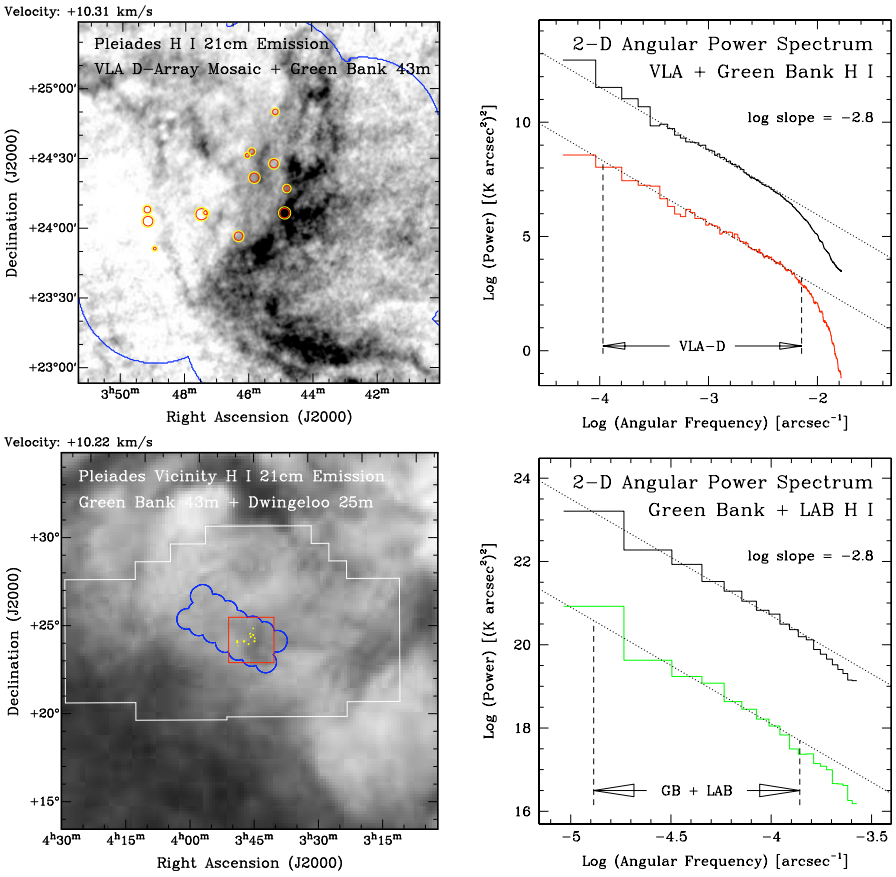

Figure 3. Pleiades H I 21cm-line emission, negative scale. Bright stars and Schmidt mosaic boundaries are shown for reference. *Top left:* 192-field mosaic using the D-configuration Very Large Array (VLA-D), with short spacings provided by the Green Bank 43m telescope (Gibson et al. 1995). Linear intensity scale. *Bottom left:* Full Green Bank map (white contour) padded to 128x128 GB pixels with Dwingeloo - Leiden/Argentine/Bonn (LAB) 25m data (Kalberla et al. 2005) for FFT analysis. VLA area is small square. Logarithmic intensity scale. *Right panels:* Angular power spectra. The lower spectra are for single channels with $v_{lsr} = +10$ km s^{-1}; the upper spectra are integrated over the H I line.

Schmidt spectrum deviates from the power law, probably because the stellar illumination pattern is becoming more important than the observed dust density structure. For scales larger than the cluster core, the spectrum flattens in the absence of additional illumination structure. Similar "illumination bias" behavior is observed in power spectra of the smooth nebular models of Gibson & Nordsieck (2003b), at both optical and far-infrared wavelengths. The FIR model results indicate that, unfortunately, 100 μm maps from the *Infrared Astronomical Satellite (IRAS)* cannot be used to study multiscale structure in the Pleiades, because the 5′ *IRAS* beam is too close to the illumination scale.

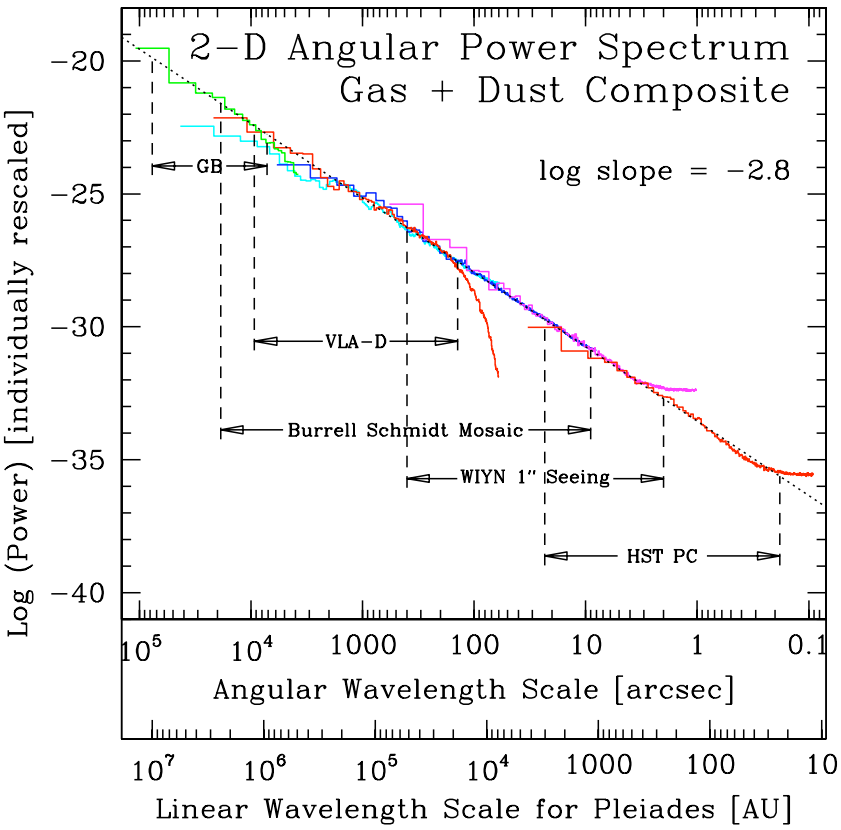

Figure 4. Composite of the optical and H I angular power spectra shown in Figures 1-3. The relative scalings have been adjusted to fit a uniform power law, but the slope of each spectrum is unaltered. The dashed lines mark ranges of measurement for each data set. "Wavelength" = 1/spatial frequency. The maximum wavelength of any image is the image width, and the minimum is either twice the beam width or twice the pixel width, whichever is greater.

The HST results are surprising. While some of the long, parallel streamers in the map are probably part of the larger nebular structure visible in the WIYN image, the bright structure in the HST map is from IC 349, an intense 20″ clump whose dynamical relation to the larger Pleiades nebulosity is controversial (Barentine & Esquerdo 1999; Herbig & Simon 2001; White 2003). IC 349 has the appearance of a lumpy, limb-brightened, optically-thick cloud, while most Pleiades optical nebulosity resembles smooth, optically-thin filaments. Thus it seems unlikely that IC 349 is typical of nebular structure elsewhere in the Pleiades at these scales. Yet the HST power spectrum is quite similar to the WIYN and Schmidt spectra. It is hard to understand this result unless the power spectrum is relatively insensitive to morphology.

The H I power spectra are preliminary, as they have not yet been corrected for possible noise contamination. But if noise is not significant, as is probably

true for at least the single-dish data, then the H I and dust slopes agree well enough to suggest a single power law for both, even at scales larger than that of the Pleiades nebulosity. This could indicate that the Pleiades ISM structure is the same as the more general ISM, which is consistent with the nebula merely being a chance illumination of ordinary interstellar material. On the other hand, there is no apparent difference in the slope of single-channel H I emission vs. that integrated over all relevant velocities, which does not agree with the theoretical predictions of Lazarian & Pogosyan (2000) for the general ISM. In any case, when combined, all of the Pleiades power spectra appear consistent with a single power law over 5 orders of magnitude in angular and physical scale.

4. The Next Step: H I Self-Absorption Structure

Near the Galactic plane, where dust and H I emission are more confused, H I self-absorption (HISA) may serve as a useful cold gas tracer (e.g., Gibson et al. 2005). A HISA power spectrum investigation is underway.

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References

Barentine, J. C., & Esquerdo, G. A. 1999, AJ, 117, 1402
Breger, M. 1987, ApJ, 319, 754
Černis, K. 1987, Ap&SS, 133, 355
Deshpande, A. A., Dwarakanath, K. S., & Goss, W. M. 2000, ApJ, 543, 227
Dickey, J. M., McClure-Griffiths, N. M., Stanimirović, S., Gaensler, B. M., & Green, A. J. 2001, ApJ, 561, 264
Gautier, T. N., III, Boulanger, F., Pérault, M., & Puget, J. L. 1992, AJ, 103, 1313
Gibson, S. J., Holdaway, M. A., & Nordsieck, K. H. 1995, AAS, 187, #45.13
Gibson, S. J., & Nordsieck, K. H. 2003b, ApJ, 589, 362
Gibson, S. J., & Nordsieck, K. H. 2003a, ApJ, 589, 347
Gibson, S. J., Taylor, A. R., Higgs, L. A., Brunt, C. M., & Dewdney, P. E. 2005, ApJ, 626, 195
Gordon, K. J., & Arny, T. T. 1984, AJ, 89, 672
Green, D. A. 1993, MNRAS, 262, 327
Guhathakurta, P., & Cutri, R. M. 1994, ASP Conf. Ser. 58, *The First Symposium on the Infrared Cirrus and Diffuse Interstellar Clouds*, eds. R. M. Cutri & W. B. Latter, p. 34
Herbig, G. H., & Simon, T. 2001, AJ, 121, 3138
Kalberla, P. M. W., Burton W. B., Hartmann, D., Arnal, E. M., Bajaja, E., Morras, R., & Pöppel, W. G. L. 2005, A&A, 440, 775
Lazarian, A., & Pogosyan, D. 2000, ApJ, 537, 720
Percival, S. M., Salaris, M., & Groenewegen, M. A. T. 2005, A&A, 429, 887
Press, W. H., Flannery, B. P., Teukolsky, S. A. & Vetterling, W. T. 1988, *Numerical Recipes in C: The Art of Scientific Computing* (Cambridge: New York)
White, R. E. 2003, ApJS, 148, 487
White, R. E. 1984, ApJ, 284, 685