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The First Detection of Diffuse Interstellar [OII] Emission and Confirmation that Variations in [NII]/Hα Trace Variations in Temperature

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Overview:

Using a newly developed Spatial Heterodyne Spectrometer (SHS), we have obtained the first radial velocity resolved emission-line profiles of diffuse [OII] λ3726 and λ3729 doublet emission from the warm (10^4 K) ionized component of our Galaxy's interstellar medium (WIM). These [OII] lines are a principal coolant for this widespread, photoionized gas and are a tracer of variations in the gas temperature resulting from unidentified heating processes that appear to be acting within the Galaxy's disk and halo.

Introduction:

Variations in the [NII]/Hα and [SII]/Hα line intensity ratios suggest that there are significant (ΔT ~ 3000 K) variations in temperature within the warm ionized medium (WIM or DIG) that permeates the disk and halo of spiral galaxies (e.g., Haffner et al., 1999; Tullmann & Dettmar, 2000). If such temperature variations are real, they would imply substantial (factors of 2 to 3) differences between one location and another in the heating and/or cooling rates within the gas (or alternatively, factor of 3 differences in the interstellar abundance; see Osterbrock, 1989).

The Crucial Test Provided by [OII] λ3727:

Because of the potentially profound consequences for understanding heating and ionization processes within the Galactic halo, it is important to develop the ability to verify that variations in [NII]/Hα and [SII]/Hα within the interstellar medium are in fact due to temperature variations, and not the result of peculiar ionization effects. A definitive method of discrimination would be measuring and comparing the associated variations in [OII]/Hα and [NII]/Hα. The [OII] transition results from thermal electron excitations to the doublet D state of O^+, 3.3 eV above ground. Since this excitation energy is significantly larger than that of the red [NII] and [SII] lines (1.9 eV), variations in electron temperature will result in a significant (and quantitatively predictable) variation in the [OII]/Hα and [NII]/Hα intensity ratios. This is illustrated in Figure 1. The O^+ ion is the dominant ion of oxygen in the diffuse ionized gas (with O^+/O near unity as implied both by observations of [O I] and [OIII] and by models) as well a primary forbidden line coolant. This means that the [OII] will be relatively bright, comparable to the Hα, and that any variations in the ratio [OII]/Hα are the result of variations in the temperature, not the ionization state of oxygen; the hydrogen is nearly fully ionized within this medium (Reynolds et al., 1998). Thus the postulated variation in T_e derived from [NII]/Hα (Haffner et al., 1999) can be verified (or refuted) by measuring and comparing the associated variations in [OII]/Hα and [NII]/Hα.

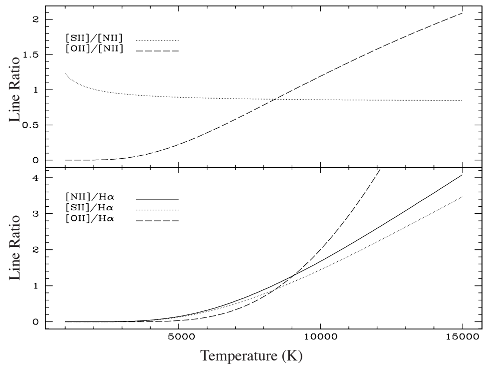

Figure 1: Emission line intensity ratios versus electron temperature T_e for low density, ionized interstellar gas in which the ionization fractions H^+/H, N^+/N, S^+/S, and O^+/O are unity. Solar abundances were used; i.e. $N/H = 9.1 \times 10^{-5}$, $S/H = 1.6 \times 10^{-5}$, $O/H = 6.6 \times 10^{-4}$ (Allen, 1991). (courtesy of B. Otte)

Furthermore, discrepancies between [OII]/Hα and [NII]/Hα can be used to explore possible variations in the ionization state of nitrogen. No other lines of comparable intensity exist for this study.

Otte et al. (2002) have already carried out such observations for a number of edge-on spirals with encouraging results --for example, they found strong evidence for temperature variations within the ionized halo gas in NGC 5775 and NGC 891 (Tulleman & Dettmar, 2000). Although these extragalactic observations provide support for temperature variations in the ionized gas, extending the [OII] observations to the Milky Way is a necessary step for verification of these processes. This is due in part to the fact that the observations of the edge-on galaxies correspond to path lengths of about 10 kpc; such lengths are necessary to build up the line intensity to a level that can be detected with slit spectrometers on a moderate-sized telescope. By integrating across most of a galaxy's disk, the data represent the sum over a potentially wide variety of different physical conditions within the emitting gas. Corrections for interstellar extinction as well as Fraunhofer absorption features in the underlying stellar continuum are sources of additional uncertainty in interpreting the spectra of edge-on galaxies. From our position within the Milky Way, observations at moderate Galactic latitudes with sufficiently high spectral resolution and with sufficiently high sensitivity allow one to resolve kinematically relatively small portions of the Galaxy, without ambiguities associated with the superposition of different areas of the Galaxy along the line of sight. Also, because path lengths are relatively short and observations can be made away from the Galactic plane, extinction is minimal.

The Spatial Heterodyne Spectrometer:

Because the [OII] λ3726-9 lines are well outside the wavelength range accessible to WHAM, with support from the NSF we designed and built a Spatial Heterodyne Spectrometer (SHS) capable of detecting and resolving the diffuse interstellar [OII] emission lines; refer to Figure 2.

SHS is a relative of Michelson Fourier Transform Spectroscopy in which the return mirrors are replaced by stationary diffraction gratings operating near Littrow wavelength (in this case λ3727). The resulting interferogram is imaged on an imaging detector and Fourier Transformed to recover the original spectrum (Harlander et al., 1992). SHS is field-widened with the insertion of fixed prisms in each arm, giving the spectrometer an enormous throughput gain over conventional systems of similar size and resolving power, comparable in sensitivity to WHAM. The resolving power is ~30,000 (~10 km/s).

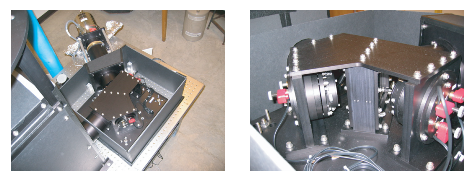

Figure 2: (*left*) Top view of the [OII] SHS interferometer. (*right*) Side view of the [OII] SHS interferometer.

observations, results, conclusions

Observations & Results:

We carried out velocity-resolved observations of the [OII] doublet emission over a region of the sky already mapped by WHAM in [NII] λ6584 and Hα (λ6563). A series of 10 minute exposures toward target science directions are interspersed with exposures toward high Galactic latitude regions where very little interstellar [OII] emission is expected. This "on-off" technique is used to identify terrestrial emission, which includes [OII] in addition to other airglow lines; refer to Figure 3.

Our observations confirm the superb performance of the SHS technique for measurements of spatially extended faint emissions, including the first detection of diffuse [OII] emission extending out to 20° from the Galactic equator in the longitude range of 110 to 150°. [OII] intensities range from tens of Rayleighs near the Galactic plane to less than one Rayleigh at high Galactic latitudes (Mierkiewicz et al., 2006). The [OII] line profiles clearly show structure indicating emission along the lines of sight from both local interstellar gas and more distant gas Doppler shifted by differential Galactic rotation; refer to Figure 3.

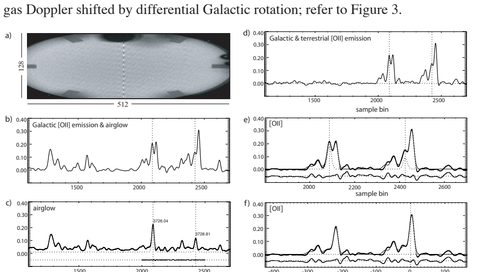

Figure 3: Example [OII] SHS spectra. (a) An example interferogram from a 2° field centered at Galactic latitude b=-12.7° and longitude l=135.1°; the CCD is binned 1 by 4 in order to reduce the number of reads in the non-dispersive (i.e., y) direction. (b) Partial slice in x of the power spectrum of the two-dimensional Fourier transform of (a); the vertical dotted lines in b-e indicate the position of terrestrial [OII] emission. (c) SHS spectrum of a negligible Galactic [OII] emission region. (d) Region l =135.1°, b=-12.7° with the atmospheric foreground emission (excluding the terrestrial [OII]) removed. (e) Fitted [OII] emission (solid line). (f) Diffuse Galactic [OII] emission free of terrestrial contributions; emission along the lines of sight from both the local and more distant gas in the Perseus spiral arm (Doppler shifted ~ 40 km/s to the blue), is apparent; the velocity scale is referenced to the λ3729 line of the doublet. The total [OII] emission in (f) is ~ 5 R.

Line Ratios:

Line ratio comparisons of the SHS [OII] spectra with WHAM spectra of [NII] and Hα confirm the value of the [OII] observations as a diagnostic for variations in temperature within the diffuse ionized gas. This is illustrated in Figure 4 which shows spectra of [OII] toward two directions obtained with the SHS (4a and 4d) compared to spectra of [NII] (4b and 4e) and Hα (4c and 4f) obtained with WHAM. The higher [OII]/Hα and [NII]/Hα line intensity ratios for the low velocity component (near 0 LSR) toward l=136.1°, b=-13.6° compared to that toward l=150.4°, b=-10.2° suggest that the component toward the former direction has a substantially higher temperature than that toward the latter direction. Not only are [OII]/Hα and [NII]/Hα both higher toward l=136.1°, b=-13.6°, but the enhancement in [OII]/Hα is greater than that in [NII]/Hα, just as predicted if the line ratio variations are due to variations in temperature (the excitation energy for [OII] is significantly higher than that for [NII]).

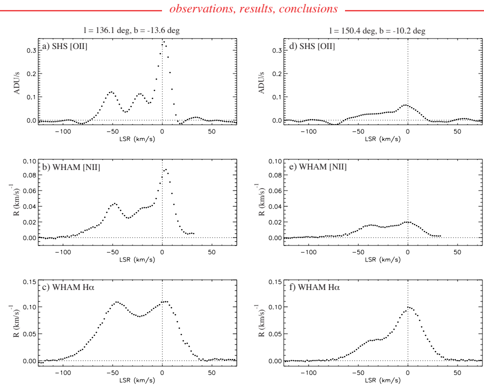

Figure 4: SHS [OII] spectra and WHAM [NII] and Hα spectra toward two directions that sample warm ionized gas in both the local and Perseus spiral arms. Toward l=136.1°, b=-13.6° (*left*) the spectra clearly show that the local gas (component near 0 km/s) has elevated [OII]/Hα and [NII]/Hα, implying a higher temperature, compared to the local component toward l=150.4°, b=-10.2° (*right*). Intensity scales for the WHAM Hα and [NII] observations are in R $(km/s)^{-1}$; the SHS [OII] intensity is in arbitrary units (but consistent between [OII] spectra).

This conclusion is borne out quantitatively. In Figure 5, observations of [OII]/Hα are plotted versus [NII]/Hα for the low velocity (local gas) components toward 7 diffuse emission regions between l=130° and l=150° with latitudes between -6° and -14°, and two bright classical O star HII regions. This plot shows a clear relationship between [OII]/Hα and [NII]/Hα that closely follows that predicted by variations in temperature (solid line). The solid line in Figure 5 is from the relationships:

$$[NII]/H\alpha = 9.76\, T_4^{0.428}\, e^{-2.18/T_4} \quad \text{and} \quad [OII]/H\alpha = 66\, T_4^{0.428}\, e^{-3.87/T_4}$$

which are derived assuming standard gas phase abundances and ionization ratios O^+/O and N^+/N that are 1.0 and 0.8, respectively. Because we have not yet carried out an accurate absolute intensity calibration for our [OII] measurements, the curve in Figure 5 has been normalized to the data at [NII]/Hα ~ 0.52, corresponding to a temperature of 7700 K. The associated temperatures are also plotted.

The excellent correspondence between the variations in the observed line ratios and the relationship predicted by changes in temperature provides convincing evidence that, for these data at least, the variations in line ratios are dominated by variations in temperature within the ionized gas. Note that because the ionization potential of N^+ (29 eV) is significantly less than that of O^+ (35 eV), the elevated [OII]/Hα (relative to the predicted temperature curve) at low [OII]/Hα and [NII]/Hα (directions 6 and 7 in Figure 5) could be an indication of ionization effects in which a significant fraction of N is N^{++}. In fact, directions 6 and 7 sample diffuse ionized gas near the high Galactic latitude O7 star ξPer, which could be responsible for a reduction in N^+/N in the nearby diffuse gas.

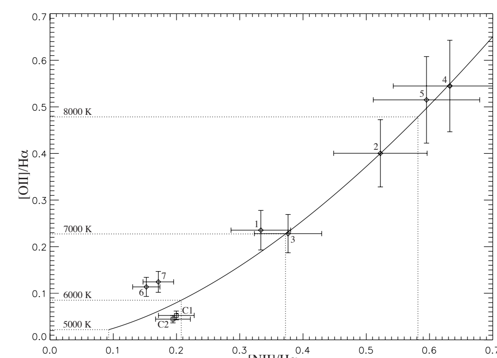

Figure 5: [OII]/Hα vs. [NII]/Hα for seven diffuse emission regions (Diamond) plus two bright classical HII regions (Box). The solid curve is the relationship predicted if the line ratio variations were the result of temperature variations only. The [OII]/Hα ratio has been normalized to the data at [NII]/Hα = 0.52, corresponding to a temperature of ~7700 K, pending absolute intensity calibration for our [OII] measurements.

Conclusion:

The detection and study of diffuse interstellar [OII] λ3726-9 emission has provided strong evidence that the large variations observed in [NII]/Hα and [SII]/Hα intensity ratios are the result of significant (ΔT ~ 2000-3000 K) temperature variations within the diffuse ionized gas of the Milky Way. The reason for these temperature variations is not yet known.

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