Mid-Infrared Emission at Photodissociation Regions in the Orion Nebula

Marc Kassis

Keck Observatory, 65-1120 Mamalahoa Highway, Kamuela, HI 96743

mkassis@keck.hawaii.edu

Joseph D. Adams

Cornell University, 206 Space Science Bldg., Ithaca, NY 14853

Murray F. Campbell

Colby College Department of Physics & Astronomy, 5863 Mayflower Hill, Waterville, ME 04901

Lynne K. Deutsch, Joseph L. Hora

Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

James M. Jackson

Boston University Astronomy Dept. 725 Commonwealth Ave., Boston, MA 02215

and

Eric V. Tollestrup

University of Hawaii, NASA Infrared Telescope Facility, 640 N. Aohoku Pl. #209, Hilo, HI 96720

ABSTRACT

1Visiting Astronomer at the Infrared Telescope Facility, which is operated by the University of Hawaii under a cooperative agreement with the National Aeronautics and Space Administration.

2Prior to her death in April 2004, the Principle Investigator of the MIRSI, Lynne K. Deutsch, made contributions to results presented in this paper.
The mid-infrared emission from a photodissociation region (PDR) viewed edge-on in the Orion Nebula is examined through 8.7-20.6 μm images and 8-13 μm spectra. Using a simple model, the spatial variations in the emission from polycyclic aromatic hydrocarbons detected at 8.6, 11.2, and 12.7 μm are demonstrated to be directly proportional to the material column density and the intensity of the UV field. For a homogeneous, neutral cloud illuminated by a bright OB star, PDR theory predicts that the ultra-violet (UV) radiation is attenuated exponentially \( e^{-1.8A_v} \). The predicted UV attenuation is confirmed by observations of broad emission features found at 8.6, 11.2, and 12.7 μm, commonly attributed to emission from polycyclic aromatic hydrocarbons (PAHs). The PAH emission is located between the edges of H II regions and layers of \([C I]\) emission, agreeing with PDR theory. Through modeling we determine a gas density of \( 9.7 \times 10^4 \text{cm}^{-3} \). On large and small size scales, the relative strengths of the 8.6, 11.2, and 12.7 μm PAH features at the bar of the Orion Nebula indicate that there is not a simple transition from ionized to neutral PAHs across the PDR.

Subject headings: H II regions, ISM: individual (Orion Nebula), dust

1. Introduction

In the Orion Nebula (M42, NGC 1976), radiation from bright OB stars ionize the surface of the nearby Orion molecular cloud, (OMC-1), to form a blister H II region viewed predominantly face-on (O'Dell 2001). The H II region is 0.1 pc thick (O'Dell 2001) and 1 pc in diameter at a distance of 450 pc. Situated on the surface of the molecular cloud, the main ionization front (MIF) is concave toward the observer and the four ionizing OB stars known as the Trapezium. The MIF is primarily due to radiation from the brightest member of the Trapezium, \( \theta^1 \) Ori C, except for a few isolated emission features such as the ring-shaped Ney-Allen nebula located near and illuminated by \( \theta^1 \) Ori D (O'Dell 2001).

A bright, linear structure known as the bar is located 2′ southeast of the Trapezium. The bar extends 4′ from the northeast to the southwest (Schoen & Loren 1982) and is a region where the geometry of the MIF changes from face-on to edge-on. The bar is 0.1-0.6 pc thick (Hogerheijde et al. 1995; Jansen et al. 1995; Simon et al. 1997; Werner et al. 1976; Tauber et al. 1994) and is composed of \( \sim 1-5 \times 10^4 \text{cm}^{-3} \) dense gas (Hogerheijde et al. 1995; Jansen et al. 1995; Tauber et al. 1994) containing \( 3 \times 10^6-4 \times 10^6 \text{cm}^{-3} \) clumps with sizes of a few arc-seconds (Hogerheijde et al. 1995).
At the Orion bar, the material is clearly stratified, and in general, the location of ionized, neutral atomic, and molecular material agrees well with models of dense photo-dissociation regions (PDRs) (Hollenbach & Tielens 1999). Recent PDR theories include the effects of polycyclic aromatic hydrocarbons (PAHs), large molecules that are generally accepted as the carriers of a family of bright infrared emission features known as the Unidentified Infrared (UIR) bands with primary features at 3.3, 6.2, 7.7, 8.6, 11.2, and 12.7 μm. With sizes greater than 50-C atoms (Hony et al. 2001), PAH molecules may represent the smallest grains in the ISM (Draine & Lazarian 1998), and because they are numerous (Draine & Lazarian 1998), PAHs may be a significant source of attenuation of UV photons (Bakes et al. 1994, 1998). Throughout this paper, we refer to emission features at 3.3, 6.2, 7.7, 8.6, 11.2, and 12.7 μm as "PAH features", but recognize that the carriers have not been definitively identified.

Because the Orion Nebula is located relatively near the Sun at a distance of 450 pc (Bally et al. 2000 and references therein), the structure of the photo-dissociation region and the role played by PAHs at the bar may be probed on small spatial scales. In order to study the variation of the PAH emission features across a PDR, we used the Mid-Infrared Spectrometer and Imager (MIRSI: Deutsch, et al. 2002, Kassis, 2004) to obtain images and spectra of the Orion bar. The images and spectra are used to place the spatial variations of the PAH features in context with other tracers of PDR structure. In section two, the observations and reduction methods are described. Section three presents the images and spectra. A model that predicts the PAH emission features is presented in section four. Section five discusses PAHs at the Orion bar before summarizing the results.

2. Observations and Reductions

We acquired images and spectra that measure emission from the Orion bar and surrounding structure using MIRSI (Deutsch, et al. 2002) during October and November 2002. Images were acquired at 8.7, 11.6, and 20.7 μm using 10% bandwidth discrete filters and at 10.5, 10.8, and 11.2 μm using a Circular Variable Filter (CVF) (5% bandwidth). The CVF was used to measure the continuum emission at 10.8 μm and isolate 11.2 μm PAH emission and emission from ionized gas at [S IV] 10.51 μm. At 1.6 and 20.7 μm, additional images were obtained to make mosaics extending north of the bar through Trapezium and to the BN/KL region.

Using the 10 μm grism with the N-band filter as a blocking element, spectra were acquired at two spatial locations along the bar. The length of the slit on the sky was 64" and was aligned north-south. The slit centers were located at 5h35m20.7s, -5°25'07" and 5h35m22.4s, -5°25'01" (J2000) and are called positions one and two, respectively. The
spectra were measured from 8-13 μm with a resolution of R=100. At R=100, we were able to resolve PAH emission bands. The on-source integration time for the observations is summarized in Table 1.

The telescope was operated in a chop-nod mode to remove the emission from the sky and telescope. Chop and nod throws were set at 2' south and 4' east, respectively. In the northernmost images in the mosaics at 11.6 and 20.7 μm, which includes the BN/KL region, emission from the bar is present in the off-source chop beam. The diffuse emission near BN/KL is of order 10 times brighter than the emission from the bar, therefore, the gross features in the BN/KL region are not significantly effected by the bar structure mapped in the off-source chop beam.

2.1. Reduction Process of the Mid-Infrared Images and Spectra

Data obtained of the Orion Nebula and the standard stars were reduced in the following way. Chop and Nod images were subtracted from the on-source image, and then a pattern noise was removed from the differenced image. The noise pattern repeated in each of the 16 readout channels, and for point sources, median filtering across the channels is used to remove the pattern noise (Kassis, 2004, Kassis et al., in preparation).

In addition to the pattern noise, a channel bias was subtracted. The median channel value was subtracted from all pixels in a channel for images of point sources. For diffuse emission sources, the average of the lowest quarter of intensities in each channel was the estimated channel bias. Again, the lowest quarter of intensities is assumed to sample primarily the background emission.

Both dome and sky flat fields were acquired. Gain maps were created by subtracting images of the sky from those of the dome and dividing by the mean. Source images were then divided by gain maps to flatten the fields.

Image fluxes for sources and standards were corrected for the observed airmass of the object using the standard extinction coefficients for the IRTF (Krisciunas et al., 1987). Extinction coefficients calculated from the observations of α Tau at 11.6 μm agreed with the standard values. Extinction corrections were not applied to grism spectra because the absolute fluxes are not required to compare the location and spatial variation of the mid-infrared emission features.

To create a bad pixel map, gain maps were sub divided into 10x10 pixel images to avoid flagging vignetted pixels in the corners of the array. The mean and standard deviation in
each sub-image were calculated after rejecting the 10 highest and 10 lowest valued pixels. Pixels with gain values more than 10 standard deviations from the mean were identified as bad pixels.

To remove granular pixelation effects from the images, a dither pattern was used to offset the telescope by a few arc-seconds between exposures. The images were co-added by applying a standard dither pattern after correcting for telescope drift. For the standard stars, the drift from image to image was corrected by aligning the images by the point spread function center. For the mosaics of the Orion Nebula, a drift rate was calculated from bracket observations of the BN/KL object. The position of BN/KL on the detector was observed to drift from image to image at a rate of 0.4-0.5 per image, or 1-2 pixels at a scale of 0.265''/pixel. For CVF images of the bar, co-added images were combined using only the amount dithered between images.

Images were combined using standard procedures in IRAF. Mosaics were built for each night before combining images from all nights. The relative intensities between images were determined from the regions of overlap (typically the BN/KL region). The relative intensities of the mosaics at 20.7 μm from observations on Nov. 6 and 7 were scaled to those measured from images acquired Nov. 1.

2.2. Flux Calibration

Observations of the infrared standard star α Tau were used to calibrate images and spectra of the Orion bar. Fluxes from α Tau at all observed wavelengths were measured using an artificial aperture with a radius of 3.3. The average background flux was calculated from the flux measured in an annulus of 5.3-8.0 from the standard star peak intensity and subtracted. The assumed flux for α Tau for each filter passband was acquired from the MIRSI standard star list\textsuperscript{1}, which is based on an accepted mid-infrared spectrum presented by Cohen et al. (1992).

The total flux from α Tau was not measured in grism spectra because the telescope drift carried α Tau in and out of the slit. Only spectra with observed fluxes of > 1000 ADUs at 10 μm were combined. The spectra were extracted using the APALL routine in the IRAF package. The spectrum of α Tau provided in Cohen et al. (1992) was interpolated to match the R=100 8-13 μm spectra obtained with MIRSI. The observed α Tau spectrum was divided by the interpolated spectrum to determine the relative calibration as a function\textsuperscript{1}

\textsuperscript{1}see the MIRSI home page at http://cfa-www.harvard.edu/mirsi/
of wavelength. The calibration is not absolute because the total flux from α Tau was not measured. Finally, the observed spectra from the bar were divided by the relative calibration spectrum of α Tau.

At slit position one, an 8.7 μm image acquired immediately before the spectra is used to scale the calibrated spectrum of the bar. The slit width is 1.″6 on the sky corresponding to six instrument pixels. The flux at 8.7 μm from the image was measured using an artificial aperture 1.″6 arcsec in width and 2.″7 in length along an area that measured the brightest 8.6 μm PAH emission. The flux from the bar was measured spectrally between the Half-Power-Points (HPPs) of the 8.7 μm filter and spatially along the same 2.″7 aperture length as described above. The spectrum at position one was then scaled by the ratio of the 8.7 μm flux measured from the image to that measured from the spectrum. The same procedure to correct the flux in the spectrum acquired at position two was followed except that the reference image was taken at 11.6 μm instead of at 8.7 μm.

The signal to noise in both spectra is worse at the shortest and longest wavelengths. The poor sensitivities are a result of the blocking element used in combination with the grism. The blocking element is the N-band filter with HPPs at 8.2 and 13 μm. The atmospheric transmission hampers observations at 9.5-10.0 μm which results in lower sensitivities at those wavelengths as well. The highest signal to noise is from 10-12.5 μm.

The wavelength coverage and dispersion were determined using forbidden lines in the spectra acquired of the Orion bar at 10 μm. Ionized gas [Ar III] 8.99, [S IV] 10.51, and [Ne II] 12.81 μm were observed in the spectra. A gaussian adequately fit the line profiles, and had a width of 3.76 pixels (1.6 sigma). From a linear fit to the location of the three lines, the spectral range is 8.0 - 13.9 μm with a dispersion of 0.01866 μm/pix.

3. Mid-Infrared Images and Spectra

The three most prominent features of the Orion Nebula observable at infrared wavelengths, the bar, the Trapezium, and the BN/KL region, are detected at 11.6 and 20.7 μm (see Figures 1 and 2). The BN/KL region is located in the northwest corner of the mosaics. In the 11.6 and 20.7 μm mosaics, the intensity scale is set to show the faint diffuse emission from the bar. As a result of the intensity scaling, the details of the BN/KL region are lost. Figure 3 is an enlarged section of the 20.7 μm mosaic with an intensity scale that shows the details of the BN/KL region. Several point sources are detected in the image that have previously been identified at near and or mid-infrared wavelengths, see eg. Becklin & Neugebauer (1967); Kleinmann & Low (1967); McCaughrean & Gezari (1991); Dougados et
al. (1993); Gezari & Backman (1994); Gezari et al. (1998); Lonsdale et al. (1982); Shuping et al. (2004) and references therein. The well known BN/KL object (Becklin & Neugebauer 1967; Kleinmann & Low 1967) is the brightest point-like source in the region. Throughout this paper, positions are provided relative to the BN/KL object.

The Ney-Allen nebula is located near the Trapezium at 45" East and 50" South of the BN/KL object. In the mid-infrared mosaics, several bright, diffuse sources are located within 30" of the Trapezium. These diffuse sources are fainter than the objects located in the BN/KL region, but are relatively brighter than the emission from the bar located 2' southeast of the Trapezium. Because θ1 Ori C is primarily responsible for heating both regions, the emission from the bar is relatively weaker due to the distance from the Trapezium. In the mid-infrared mosaics, the bar extends ~2.5' from northeast to southwest at mid-infrared wavelengths, with the brightest section located near θ2 Ori A at 131", -154" relative to the BN/KL object.

3.1. Source Identification and Optical Counterparts

In Figures 1 and 2, there are several features that have optical counterparts. Figure 4 shows the relation between H-alpha emission mapped with the Hubble Space Telescope (HST) and emission at 20.7 μm. The BN/KL region does not correspond with bright optical emission (Becklin & Neugebauer 1967; Kleinmann & Low 1967).

Along the length of the bar, several patches of mid-infrared emission are located south and east of bright H-alpha components (see Figure 4). The brightest section of the bar shows that the H-alpha mapped by HST is adjacent to the mid-infrared emission imaged at 20.7 μm. The offset between the H-alpha and mid-infrared emission indicates that the emitting dust is located behind the H II region. The clear separation between the optical and mid-infrared also suggests that the material at the bar is viewed edge-on. Fainter bar components located at 160", -100" and 30", -200" exhibit the same spatial relationship between the H-alpha and mid-infrared emission indicating that the edge-on geometry persists along the length of the bar.

In contrast to the emission found at the bar, the mid-infrared emission located near the Trapezium coincides with bright HST features. The Orion S region located 30" southwest of the Trapezium exhibits spatial variations of O I, H I, [Fe II], and H2 implying geometries that are inclined along our line of sight Luhman et al. (1998). The spatial agreement between the mid-infrared and H-alpha emission argues against an edge-on geometry in this region. The spatial agreement between the mid-infrared and H-alpha maps near Orion S combined
with the relatively low visible extinction toward the Trapezium and Orion S (O’Dell & Wong 1996) means that the mid-infrared bright material is located behind the H II region along the observer’s line of sight.

Bally et al. (2000) identify a dark lane which is not associated with ionization ratio fluctuations that are typical for the linear structures like the bar. Located south of the Orion S and the Trapezium regions, the dark lane is not associated with optical extinction (O’Dell & Wong 1996). The region of the dark lane has relatively little mid-infrared emission associated with it as seen in Figure 4. The dark lane may be a depression in the MIF where the UV field does not impinge upon neutral material.

Shocks and jets are common in the Orion Nebula (O’Dell et al. 1997; Bally et al. 2000), and a handful of mid-infrared features are coincident with Herbig Haro (HH) flows. At the bar, HH203 and HH204 are detected at mid-infrared wavelengths. Both HH203 and HH204 are bow shocks propagating to the southeast (O’Dell et al. 1997). Flows HH202 and HH529 are propagating north and east, respectively, from OMC1-S. Last, the collimated outflow propagating southeast from OMC1-S (O’Dell et al. 1997), is detected. The emission from the detected shocks is similar to the shape of the optical emission in HST images outlined in Figure 2 of (Bally et al. 2000).

3.1.1. Proplyds

In the Orion Nebula, proplyds are observed toward young, low-mass stars (O’Dell & Wong 1996). The term proplyd applies to circumstellar material in the form of a protoplanetary disk (see O’Dell (2001) and references therein). Radiation from θ² Ori C and the central low-mass star heats grains in the disk which re-radiate at mid-infrared wavelengths.

Over 150 proplyd positions taken from the lists of O’Dell & Wong (1996) and Bally et al. (2000) were overlaid on the 11.6 and 20.7 µm mosaics. Many proplyd positions are coincident with MIR emission. There are several extended mid-infrared bright features within 30″ of the Trapezium, each with proplyds located within a few arcsec. An isolated example is the giant proplyd 244-440 that has an optically dark disk surrounded by optical emission. The proplyd 244-440 is located southeast of the bar, 153″, -138″ from BN/KL, in a relatively dark region in the 11.6 and 20.7 µm mosaics. At 20.7 µm, it is only marginally detected above a one sigma level.
3.1.2. New Sources

A few new sources are identified at 11.6 and 20.7 µm. There are two mid-infrared point sources with no known counterpart at other wavelengths. The two objects are located at 5h35m19.5s, -5°25'44" and 5h35m11.6s, -5°23'41" (J2000) or at relative offsets from BN/KL of 79", -201" (south of the bar) and -43", 60" (west of BN/KL), respectively. There is also a source located at 5h35m14.0s, -5°23'41" (J2000) near OMC1-S, and may be associated with a near infrared source (see Bally et al. (2000) and references therein).

Two new diffuse emission structures are also detected. The first is located at 5h25m26.4s, -5°25'03" (J2000: see Figure 1) and is near a star roughly 50"east of θ² Ori A. The second is located at 5h35m30.2s, -5°25'50" (J2000) and is a blob of emission in the southeast corner of Figure 1.

3.2. CVF Observations

The CVF observations were acquired at the location of the brightest emission from the bar. In the CVF images shown in Figure 5, the brightest emission is toward HH203 and HH204 and the emission from the bar is fainter.

The three CVF positions were selected to detect the emission from both gas and dust. At 10.5 µm, the emission arises from ionized gas at [S IV] 10.51 µm and the underlying continuum from warm dust grains. At 11.2 µm, continuum and PAH 11.2-11.3 µm emission is mapped. The observations at 10.8 µm map the emission from warm dust and may be used to remove the continuum emission from the images at both 10.5 and 11.2 µm.

The emission from the bar is slightly brighter at 11.2 µm than it is at either 10.5 or 10.8 µm (see Figure 5). The location of the emission at 11.2 µm is in agreement with PAH emission observed at 3.3 µm (Tielens et al. 1993; Giard et al. 1994).

The difference in emission at 10.5 and 10.8 µm shows no spatial features that lie above a three sigma detection. Because the 10.8 µm images map the continuum emission, the 10.5 µm emission arises mostly from the continuum as well. This conclusion is confirmed by the spectra obtained at positions one and two which show that the emission from ionized gas traced by the [S IV] 10.5 µm feature is confined spatially to the northernmost region in the CVF images (see section 3.3).

Because the 10.5 and 10.8 µm images map predominantly continuum emission, the observations at these two CVF wavelengths were combined to form an average 10.6 µm emission map. The 10.6 µm map is assumed to measure the emission from warm dust grains
and is used to determine color temperatures and relative opacities along the bar (see Section 3.5).

### 3.3. Spatial Locations of Emission Mid-Infrared Features

Spectra taken at the two positions at the bar are shown in Figure 6. The PAH features at 8.6 and 11.2 μm and lines of ionized gas [Ar III] 8.99, [S IV] 10.51, and [Ne II] 12.81 μm are unambiguously detected. There is an obvious division in spatial location between the PAH features and the ionized gas. At position 1 (Figure 6a), ionized gas sharply decreases in intensity and PAH emission sharply increases in intensity at a relative offset from the BN/KL object of -157″ in declination. Toward position two (Figure 6b), the transition occurs at -134″.

All three ionized gas tracers are found at different depths at the bar (see Figure 6a), and the depths to which the tracers are detected is inversely related to the ionization potential (IP) of the species. With an IP of 21.6 eV, [Ne II] 12.81 μm penetrates the furthest. Emission from [Ar III] 8.99 μm with an IP of 27.6 eV is found to decrease in intensity at a depth slightly shallower than the [Ne II] 12.81 μm emission, and with an IP of 34.8 eV, the [S IV] 10.51 μm line emission diminishes in strength at depths several arc-seconds before either [Ar III] 8.99 μm or [Ne II] 12.81 μm emission begins to decrease. At position two, emission from [S IV] 10.51 μm is not detected presumably because the slit length did not extend far enough north.

The total flux from two spatial regions outlined by rectangles in Figure 6a for position one is plotted in Figure 7. Two zones of emission are measured: one that includes the brightest emission from ionized gas and a second which contains the brightest PAH emission. In the ionized gas, emission from [Ar III] at 8.99 μm, [S IV] at 10.51 μm, and [Ne II] at 12.81 μm are detected. The strongest line is [Ne II] 12.81 μm, while the weakest is [S IV] 10.51 μm. The line emission from ionized gas is unresolved. In the spectrum, there are broader bumps that are ~1/3 μm in size. The broader bumps are repetitive on spectral scales equal to the width of one readout channel (20 pixels) of the MIRSI detector and are likely artifacts left over from the pattern noise removal.

In the second emission zone, four of the PAH bands are detected. Three PAH bands with central wavelengths at 8.6, 11.2, and 12.7 μm are clearly detected, and a fourth PAH feature at 7.7 μm is traced by the long emission wing that is found from 8-9 μm. From Figure 7, it is clear that the 12.7 μm PAH feature is the weakest PAH feature. The 8.6 and 11.2 μm features are the brightest, and all of the PAH features are resolved spectrally.
The 12.7 μm PAH feature is contaminated by the emission from [Ne II] 12.81 μm at the transition region between ionized gas and PAH emission. The contamination is evident in Figure 7 which shows that a weak [Ne II] 12.81 μm feature rides on the broader 12.7 μm PAH feature.

The mid-infrared feature strengths were measured by summing the intensity over a range in wavelength and subtracting a linear baseline. The baseline was determined by linearly interpolating the flux on either side of the spectral feature. Table 2 presents the spectral regions used to measure the flux of the spectral features and their corresponding backgrounds.

3.4. Relative Intensities of the Mid-Infrared Emission

Figure 8 helps place the observed mid-infrared PAH emission in the context with other tracers of PDR structure mapped by Walmsley et al. (2000) and Tielens et al. (1993). The feature strengths plotted in Figure 8 are derived using images from Walmsley et al. (2000) and Tielens et al. (1993). The spatial variations between the H$_2$ data from Tielens et al. (1993) and Walmsley et al. (2000) are in better agreement when a two arcsec offset is applied. Consequently, a 2" west offset was applied to the Tielens et al. (1993) data before plotting the relative intensities of emission features. The 3.3 μm emission exhibits a steeper increase at the same location as the PAH features observed in the mid-infrared data (Figure 8c) when the 2" west offset is applied. Tielens et al. (1993) and Walmsley et al. (2000) indicate that there is structure in the bar on the order of a few arcsec in size which may account for smaller differences in the spatial variations between the three studies.

From Figure 8a, the edge of the ionization front may be determined. Walmsley et al. (2000) demonstrate that [Fe III] 2.22 μm, Brγ, and He I 2.06 delineate the edge of the H II region. The H II region/neutral interface is sharp, transitioning from ionized to neutral material in a few thousand AU. The emission from [Ne II] 12.81 μm (see Figure 8c) exhibits similar spatial variations to the emission from [Fe III], Brγ, and He I. The location of the edge of the MIF (0.00 pc) is defined to be the position at which the [Ne II] 12.81 μm and Brγ emission begin to decrease (0.26 pc from θ$^1$ Ori C at position one and two). At both positions, the PAH emission is located behind the MIF marked by the lines of ionized gas in both the mid-infrared spectra and the near-infrared images of (Walmsley et al. 2000). In general, the PAH emission is located 0.0-0.04 pc behind the MIF.

The mid-infrared PAH emission extends slightly into the H$_2$ layer located around 0.04 pc from the MIF (see Figure 8). The observed mid-infrared PAH emission does not extend
past the peak in the [C I] 0.98 μm and CO layers. The [C I] 0.98 μm layer may define the depth to which mid-infrared PAH emission is found. Emission from PAH bands and O I 1.32 μm peak in the same location. Because photons with energies greater than 13.62 eV are necessary to ionize Oxygen, the PAH emission observed in the mid-infrared may result from the fluorescence from PAH molecules after they absorb radiation less than 13.6 eV. Although not shown, the location of the PAH emission relative to the PDR tracers mapped by Tielens et al. (1993) and Walmsley et al. (2000) is similar to the location of emission detected at position two.

There is more structure observed at position two (see Figure 9) than at position one indicating that a simple slab geometry may not describe all positions along the bar. There are two ridges of emission at the ionization front at position two that cause the [Ne II] emission to decrease and the PAH emission to increase (see Figure 9). The ridges are located at 0.0 and 0.01 pc. The ridge at 0.01 pc is not as pronounced. The intensity of the [Ne II] emission is anti-correlated with the PAH emission. Because of the low S/N at position two, discussion of the PAH band spatial variations at position two focus on the primary PAH features at 8.6 and 11.2 μm.

Both the CVF imaging and the spectrum at position two show that there is a bright continuum emission around 10 μm within a few arcsec of θ2 Ori A. Although not shown, the spatial location of the PAH features and other tracers of PDR structure is the same at position two, indicating that the PAH emission present toward position two is due to the radiation from the Trapezium and not from the nearby star θ2 Ori A. The spectrum centered at position two also measures the emission from HH203 and HH204. Toward HH203 [Ne II] 12.81 μm is detected, but [Ar III] 8.99 μm, [S IV] 10.51 μm, and PAHs are not.

The spectral profiles of the PAH features do not vary with depth into the PDR except immediately before the steep rise in the PAH emission. The profiles were measured in 2.06 intervals starting in the H II region. The depths at which the feature profiles were examined were -0.006, 0.0, 0.006, 0.011, and 0.017 pc from the MIF. The 8.6 and 11.2 μm PAH features are similar at the positive spatial locations. The line shapes are comparable to the profiles presented in Figure 7.

Immediately before the steep rise at the interface (-0.006 pc), emission from 7.7, 8.6, and 12.7 is not detected. The 11.2 μm feature is detected, but the feature profile shape is broader and the peak is shifted slightly to longer wavelengths. The difference in profile shape at 11.2 μm between the H II region and the neutral material may reflect a change in the emitting PAHs. Higher spatial resolution is necessary to confirm the change in the 11.2 feature profile.
3.5. Color Temperature and Optical Depth Maps

The dust color temperature and optical depth at infrared wavelengths were estimated using CVF images and the 20.7 \( \mu \)m mosaic. Dust color temperatures were calculated for the bar from the ratio of the flux at 10.6 and 20.7 \( \mu \)m. The derived color temperature assumes that the bar emits like a gray body at 10.6 and 20.7 \( \mu \)m, and assumes that the bar is optically thin at the mid-infrared wavelengths. An optical depth map was calculated using the flux at 10.6 \( \mu \)m and the color temperature map. The optical depth was derived from the standard graybody equations (Rybicki & Lightman 1979) and assuming the emissivity of the dust grains is proportional to \( \lambda^{-\gamma} \), where \( \gamma \) is 1.6.

The 10.6/20.7 \( \mu \)m color temperature of the bar is 100-140 K (see Figure 10). The emission southeast of the bar close to \( \beta^2 \) Ori A is hotter, but has a lower optical depth than the bar (see Figure 11). HH204 and HH203 exhibit high color temperatures and low optical depths relative to the bar. In general, higher color temperature areas have lower optical depths relative to cooler regions.

The regions of the PAH emission are from -155 to -170 and -135 to -150 at positions one and two, respectively. The PAH emitting regions of the bar are relatively cool and have large optical depths. The [S IV] 10.51 \( \mu \)m emission is found at declination offsets greater than -135\( ^\circ \) at position one and is located in regions of higher temperatures and lower opacities than the PAH emission. The emission from [Ar III] 8.99 \( \mu \)m and [Ne II] 12.81 \( \mu \)m is also located in regions of high temperatures and low optical depths. The optical depths toward [Ne II] 12.81 \( \mu \)m emission are lower than optical depths toward [S IV] 10.51 \( \mu \)m.

The trends in the temperature and optical depth toward regions exhibiting emission from [Ar III] 8.99 \( \mu \)m, [Ne II] 12.81 \( \mu \)m, and PAHs are similar to those at position one. Emission from [S IV] 10.51 \( \mu \)m was not detected at position two. Toward HH203, the [Ne II] emission located at 127, -177 in a region of low optical depth and high color temperature (T\( \sim \)140 K). In general, the emission from ionized gas is found toward relatively hot, low optical depth regions while PAHs are located in cooler, high optical depth regions.

4. Modeling the spatial variations in the PAH emission

Hogerheijde et al. (1995), Jansen et al. (1995), and Walmsley et al. (2000) are the most recent studies to have examined the bar geometry. Hogerheijde et al. (1995) and Jansen et al. (1995) measured the intensities from 18 different molecules at 53 submillimeter lines to probe the structure of the PDR. The beam for the sub-millimeter measurements was 20\( ^\prime \), and the observations taken at positions across the bar were separated by 20\( ^\prime \). The intensities
from all 18 molecules peak 30″ behind the MIF.

Increases in the line intensities at different positions along the bar were explained by assuming a MIF geometry changes from face-on to edge-on and back to face-on. Hogerheijde et al. (1995) and Jansen et al. (1995) argued that the increase in intensities is primarily due to an increase in column density, where the material is viewed edge-on. The ratio of the column densities in the face-on to edge-on region therefore set the height of the edge-on region at 0.6 pc (Hogerheijde et al. 1995; Jansen et al. 1995). Since the transition from face-on to edge-on occurs within 20″ on the sky, the inclination angle at which the edge-on region is viewed is < 3° (Jansen et al. 1995).

Because a wall of molecular material does not accurately account for the velocity field of the gas, Walmsley et al. (2000) modeled the bar as a cylindrical filament in addition to a wall viewed edge-on. Walmsley et al. (2000) used the spatial information in near-infrared spectroscopic observations of the O I 1.32 μm line emission to constrain the geometry of the bar. The O I 1.32 μm line emission is produced through fluorescence after the absorption in the ground state of a UV photons between 0.095 and 0.104 μm (Walmsley et al. 2000). Because the transition from O II to O I is expected to be less than an arcsec and the UV absorption is expected to be optically thick, the O I emission region is expected to be smaller than an instrument pixel in the near-infrared data (Walmsley et al. 2000). Any observed variations in the O I 1.32 μm emission must then be a function of the column of the material.

Based on the geometric models designed to match the column of material, Walmsley et al. (2000) conclude that the material at the bar may have a filamentary structure and that a cylinder is more plausible than a slab of molecular material viewed edge-on. The cylinder’s large radius then accounts for the sharp peak in intensity at a portion of the MIF that is closest to θ^1 Ori C. Neither geometric model completely describes the O I emission detected by Walmsley et al. (2000), which may be due to geometric deviations in either geometric model.

At 3.3 μm, the PAH emission exhibits a sharp increase at the MIF (Geballe et al. 1989; Bregman et al. 1989; Sellgren et al. 1990; Giard et al. 1994). The PAH emission is one of a few tracers that can map the inhomogeneities in a PDR immediately behind the MIF (Tielens et al. 1993; Giard et al. 1994). The spatial variations in the mid-infrared spectral features at positions one and two confirm a sharp increase detected at near-infrared wavelengths.

Below, we present a model to predict the observed spatial variations from the PAH features. This model does not distinguish between the two different geometries described above. Instead, we will demonstrate that it is unnecessary to assume a bar geometry to accurately predict the location of the spatial variations of the PAH features.
4.1. Geometric-Attenuation Model

Several of the ionized gas tracers detected in the near-infrared (ex: \( \text{Br} \gamma \), [Fe III]) exhibit similar behavior to the O I 1.32 \( \mu \text{m} \) line emission, which is determined to trace changes in the column density of the gas (Walmsley et al. 2000). Unless the thickness of the bar or foreground veil is greatly underestimated, the mid-infrared opacity is small. Consequently, spatial variations of the mid-infrared ionized gas emission are predominantly due to variations in the column density of emitting material. Because the [Ar III], [S IV], and [Ne II] spatial variations in emission are similar to those of O I, the ionized gas emission is assumed to also trace changes in the column density of the bar. In modeling the PAH emission, the [Ne II] 12.81 \( \mu \text{m} \) line emission is used to trace changes in the column density of the bar because the spatial offset between [Ne II] and O I is the smallest of the three detected tracers of ionized gas, because the [Ne II] emission exhibits similar spatial variations to that of O I, and because it is the brightest ionized gas feature observed at 10 \( \mu \text{m} \) (see Figure 7).

To model the PAH emission, a few assumptions were made. First, the slope of the [Ne II] emission at a particular location along the bar is used to measure the relative change in the column density of the material for reasons stated above. Second, the density of PAHs is constant in the neutral material. Third, the UV field is attenuated exponentially with depth into the PDR (see Hollenbach & Tielens 1999)). Fourth, the path the UV radiation travels to the surface of the bar from the Trapezium is perpendicular to the line of sight to the observer. This is correct as long as the height of the bar is much smaller than the distance between the Trapezium and the bar; however, this assumption is suspect because the height of the bar is on scale with the projected distance to the bar from the Trapezium (0.26 pc). Last, we assume that \( n_{\text{Ne}}/n_{\text{PAH}} \) is constant at the interface between the H II region and the neutral gas.

The product of the relative column density and the attenuated UV determines the intensity of PAH emission with depth into the PDR. The observed PAH emission is the sum of all products of the column density and UV attenuation. The functional form of the modeled PAH emission from the bar is

\[
I_d = \sum_{x=0}^{d+s} I_x e^{-B(x-(d+s))}
\]

where \( B \) is the attenuation coefficient with units of \( \text{pc}^{-1} \), \( d \) is the distance from \( \theta^1 \) Ori C at which intensity \( (I_d) \) is predicted, \( x \) is the distance to the MIF from \( \theta^1 \) Ori C, \( I_x \) is the measured intensity of the material at a specific location along the MIF, and \( s \) is a distance shift. Because the onset of PAH emission may not exactly coincide spatially with decreased [Ne II] emission, the parameter \( s \) is used to shift the predicted emission intensities to match
the observed PAH emission. The intensity of the emitters at a specific location ($I_x$) is proportional to the derivative of the [Ne II] emission ($I_x = L_o \times dI_{NeII}/dx$). The observations determine the values of $d$, $I_x$, and $x$, while the model constrains $s$ and $B$ to match the PAH spatial emission.

Figure 12 is an example of how the model works. UV radiation is incident on a cloud surface perpendicular to the line of sight of the observer. In the example, the cloud surface is defined by a fourth degree polynomial. Because the emission from [Ne II] is dependent on the column density of the ionized gas, the example simulates the decrease in emission from [Ne II] as a fourth degree polynomial. Whenever there is a change in intensity of [Ne II], we add a layer of PAH emission. The PAH emission decreases exponentially within each layer, because we assume UV radiation incident on a cloud surface is perpendicular to the line of sight of the observer. The summation of the predicted PAH intensity along the line of sight to the observer is then compared to the observed PAH spatial variations.

Figure 13 is the inverse of the derivative of the [Ne II] emission as a function of distance across the PDR for both position one and position two. We use as input to the model the inverse of the derivative because we assume that increases $N_{PAH}$ are proportional to decreases in $N_{Ne}$. At position one, there is an increase in column density that spans 0.0 to 0.01 pc. There are lots of small variations in the column density that indicate that the bar deviates from a simple slab or filamentary structure.

The best fitting models to the PAH spectral features were determined by searching over a parameter space and minimizing the RMS$^2$ of the residuals in the fit. The best fitting models have the lowest RMS after the data and model output were normalized to the emission peak. The model does not fit the measured intensity of the PAH emission, but rather predicts a relative intensity. For position one, the parameter search was 0-500 pc$^{-1}$ and ±0.01 pc for $B$ and the shift ($s$), respectively. The search intervals were 1 pc$^{-1}$ and 5×10$^{-4}$. For data at position two, the search range for the relative shift was reduced to ±0.05 pc.

Figure 14 shows that the best fit parameters listed in Table 3 are global minima within the range searched. Figure 14 shows that $B$ is not as well constrained as the shift. The small differences in the best fitted parameters for $B$ and $s$ may reflect different characteristics of different molecules that are carriers of the 7.7, 8.6, 11.2, and 12.7 μm PAH emission.

### 4.2. Best Fitting Geometric-Attenuation Models

The best fitting models at position one and two are presented in Figures 15 and 16, respectively. Overall, the predicted emission follows the observed spatial variations of the
PAH bands well from 0 to 0.04 pc. PDR theory predicts that the UV field is attenuated exponentially with depth into the PDR (Hollenbach & Tielens 1999). The model fits to the PAH bands at 8.6, 11.2, and 12.7 μm directly confirm this prediction of PDR theory.

A few thousandths of a parsec before the steep rise in the PAH emission, the models under-predict the emission at 7.7 and 11.2 μm. The model fits to these two PAH bands are shifted closer to the MIF (small s) and have a slightly lower fitted B than the best fitting models at 8.6 and 12.7 μm. The excess emission at 7.7 and 11.2 μm may reflect an excess in the carriers of the PAH bands and is attributed to differences in the spatial location of the carriers in the PAH features.

At 0.04 pc from the sharp increase in emission, the attenuation model predicts an excess of PAH emission at 8.6, 11.2, and 12.7 μm. The predicted excess may be explained by a number of reasons. First the PDR may not be homogeneous. A density gradient could increase the amount of emission close to the MIF and decrease the emission deeper in the PDR. Second, the assumption that the [Ne II] layer exhibits no additional structure besides the shape of the MIF may be incorrect. The ionized material may contain structure that is not bounded by the molecular cloud or an additional radiation source may complicate the emission structure.

Third, the UV attenuation may not be exponential. The exponential approximation is adopted by PDR theory from semi-analytical radiative transfer solutions and overestimates the asymptotic rate of decay for the mean intensity of the UV field (Flannery et al. 1980). To compensate for the overestimate, the best fitting models would have to inflate B to fit the brightest regions of PAH emission. The model would then overestimate the emission deeper inside the PDR.

Fourth, the radiation incident at the MIF may not be perpendicular to the line of sight. A change in the incident angle could enhance the emission near the MIF and reduce the emission at greater depths into the PDR. Because the size scale for the height of the bar relative to the distance between the bar and θ1 Ori C are roughly the same, the incident angle of the radiation relative to the line of sight is undoubtedly a function of position along the bar, making this the most likely reason for the excess emission at 0.04 pc. In addition, the long axis of the slit does not pass through the position of θ1 Ori C at either position one or two. Thus, there is likely a variation in column density at a location not sampled by the slit which contributes to the PAH emission deeper inside the PDR where the slit does measure the emission.

Overall, the attenuation model fits well, and material density within the bar may be determined from the best fits. Assuming \( \frac{N_H}{A_v} = 2 \times 10^{21} \text{ cm}^{-2} \) (Bohen et al. 1978) and
applying a correction of 1.8 to convert from A_v to A_{UV} as suggested by Bakes et al. (2001a,b),
the average density of the material in the bar is 9.7×10^4 cm^{-3} at the adopted distance to the
Orion Nebula.

From sub-millimeter observations, Hogerheijde et al. (1995) used molecular tracers to
determine the densities at the bar. Homogeneous density models could not fit the data.
Instead, an inter-clump density of 8×10^3-5×10^4 cm^{-3} accounts for 90% of the material in
the bar, with the other 10% comprised of 3×10^5-4×10^6 cm^{-3} dense clumps (Hogerheijde et al. 1995).
Taub er et al. (1994) densities of n_{inter-clump} = 1.3×10^4 cm^{-3} and n_{clump} = 10^6
cm^{-3}, with clump sizes of less than 0.025 pc. Deeper inside the molecular cloud (A_v > 5),
a density enhancement (2×10^5 cm^{-3}) is suggested by Simon et al. (1997) who determined
densities from model fits to CS and CN observations at the bar. The density constrained
by the attenuation model agree well with an average density of 1.3×10^6 cm^{-3} presented by
Hogerheijde et al. (1995).

In regions similar to the bar, the PAH emission may be used to probe for relatively large
clumps embedded in a homogeneous inter-clump medium. The models could help describe
where the clump is located relative to the MIF. If a clump is found at the MIF, PAH and
[Ne II] emission will exhibit compact emission peaks. The attenuation model, using the [Ne II]
emission as input, would over predict the observed PAH emission behind the clump. If
a clump is located deeper inside the PDR behind the MIF, a peak in emission will only
be detected in the PAH bands. In this case, the attenuation model will under-predict the
emission from a clump located behind the MIF and slightly over predict the emission behind
the clump.

Examples of these two cases may be located at 0.025 and 0.03 pc at position two (see
Figure 16. At 0.025 pc the PAH emission peak is not predicted by the model. This would
result if the clump is located inside the PDR instead of at the surface such that the [Ne II]
emission does not measure an increase in column from the clump. At 0.03 pc [Ne II] predicts
a broader shifted peak which does not match observed variation in the PAH emission. The
second clump may be in the MIF.

If clumps are located significantly behind the MIF, their contribution to the emission will
be appreciably smaller because the UV field is significantly attenuated. Small deviations from
the emission predicted by the attenuation model may be further proof of a clumpy medium.
Long slit spectra at more positions along the bar are necessary to measure a statistically
meaningful set of clump characteristics within the first few A_v.
5. PAH destruction and comparison to quantum chemical models

The primary PAH bands have very similar spatial distributions. Aitken et al. (1979) first observed these spatial similarities using spectrophotometric observations from 8-11.3 μm acquired at six spatial locations. With 6" resolution, Bregman et al. (1989) later confirmed the results of Aitken et al. (1979), and Roche et al. (1989) demonstrated that ionized gas emission decreased at the MIF while PAH emission increased. Together, these observations led to the conclusion that carriers of the 3.3, 7.7, 8.6, 11.2, and 12.7 μm PAH bands were photo-destroyed inside the H II region upon absorption of hard UV radiation (Aitken et al. 1979; Sellgren et al. 1990; Geballe et al. 1989; Roche et al. 1989; Bregman et al. 1989; Giard et al. 1994).

The sharp increase in the PAH emission within a few arcsec was attributed to a sharp increase in the carrier abundance, which may be evidence for the destruction of PAHs inside the H II region (Giard et al. 1994). The attenuation model fits to the mid-infrared PAH emission, strongly suggest that the observed PAH emission is due to a sharp increase in the column density of PAHs. The steep increase in emission from PAHs over a distance of 0.01 pc is mostly evidence of variations in the column density of the emitting material rather than the spatial scale over which PAH molecules are destroyed. If PAHs are destroyed by hard UV radiation closer to θ1 Ori C, PAH destruction rates calculated using the spatial scale of the sharply increasing PAH emission at the bar are underestimates.

It is possible to set limits on the time scales for the destruction of PAHs which will help constrain the size of the PAHs present in the H II region and molecular cloud. The MIF is advancing into the molecular cloud at a rate of 2 km/s or 2×10^{-6} pc/yr (O'Dell et al. 1993). The average shift between the [Ne II] and PAH emission determined from the model fits is 400 AU (see Table 3). If PAHs responsible for the observed mid-infrared emission detected behind the MIF are destroyed in less than 400 AU, the timescale for destruction is shorter than 1000 years. The short timescale is likely an upper limit for the destruction rate because the shift behind the MIF determined through modeling is relative to [Ne II] emission. The spatial location H II emission must be closer to the PAH emission than [Ne II] emission because hydrogen has a lower ionization potential. The peak emission at O I 1.32 μm is much closer to the peak in emission from the PAH features (see Figure 8) which further suggests that PAHs are destroyed extremely quick when exposed to photons with energies greater than 13.6 eV.

Bakes et al. (1998, 2001a,b) presents theoretical studies predicting PAH emission that attempt to constrain the nature of the PAH emitters. Bakes et al. (2001b) predict the spatial variations in the main PAH bands at the Orion bar and how the charge state and molecular structure affect the observed infrared spectrum. The predictions do not completely match
the observed spectrum because the model may only use spectra available in the database of quantum chemical and lab spectra (Bakes et al. 2001b). By comparing the mid-infrared emission to the predictions in Bakes et al. (2001b) for the Orion Nebula, a direction for future modeling of PAH emission may be established.

At the surface of the PDR ($A_v = 0$), PAH$^+$ molecules dominate the emission predicted in the infrared spectrum (Bakes et al. 2001b). PAH$^+$ molecules are more abundant at the MIF whereas PAH and PAH$^-$ molecules are more abundant deeper into a PDR (Bakes et al. 1998). PAH$^+$ molecules emit relatively more at 6-9 $\mu$m than at 3.3 and 11 $\mu$m than neutral PAHs (Allamandola et al. 1999). As $A_v$ increases, all PAHs become more neutral and or negatively charged resulting in increases in emission at 3.3 and 11$\mu$m. The ratio of the 6-9 $\mu$m emission to the emission at 3.3 and 11 $\mu$m decreases as the charge state of the molecules goes from being positive to neutral. Hony et al. (2001) suggests that the 12.7 $\mu$m emission may be attributed to emission from PAH$^+$ molecules due to a correlation with emission at 6.2 $\mu$m. If the 8.6 and 12.7 $\mu$m emission is due to PAH$^+$ molecules while the 11.2 $\mu$m feature is due to neutral PAHs, the transition from PAH$^+$ to neutral PAHs is identified by decreasing ratios at 8.6/11.2 and 12.7/11.2 $\mu$m.

The observed ratios of the PAH emission at 8.6, 11.2, and 12.7 $\mu$m at positions one and two are presented in Figure 17. A least-squares fit to the observed feature ratios presented in Figure 17 from 0.00-0.035 pc does not confirm that the ratios decrease with distance into the PDR. The slope determined through the linear fit is within two sigma of zero.

At both position one and two, the emission from 11.2 $\mu$m exhibits increased emission relative to 8.6 $\mu$m closer to the MIF. For position one, Figure 17 shows that the 8.6/11.2 $\mu$m ratio peaks 0.01 pc from the MIF. At position two, peaks in the ratios are also not found at the MIF, indicating that the PAH feature ratios do not agree with a simple transition from ionized to neutral PAHs.

Another method for predicting the trends in the ratios of the PAH features with depth is to use the parameter values determined from the best fitting attenuation model (see Table 3). If neutrals are found further inside the PDR, then the spatial shifts at 11.2 $\mu$m should be smaller than the shift necessary to fit the 8.6 $\mu$m PAH emission. The predicted spatial shift (see Table 3) does not demonstrate that the emission at 11.2 $\mu$m is located deeper inside the PDR. The 11.2 $\mu$m emission is found closer to the MIF than the 8.6 $\mu$m PAH emission, again suggesting that the relative strengths of the feature ratios are not tracing the transition from ionized to neutral PAHs.

Instead of tracing ionized vs. neutral material, the variations in the PAH feature emission may be due to changes in the molecular structure, size and or hydrogenation. The
broader profile of the 11.2 $\mu$m feature at the MIF relative to the profiles further inside the bar, may mark the region where the PAHs are eroded by the intense UV field. Higher spatial and spectral resolution near- and mid-infrared data are key toward determining the characteristics of the PAH material at the bar.

6. Summary

Mid-Infrared images and spectra are presented of the Orion bar. In large mosaics at 11.6 and 20.7 $\mu$m, several bright mid-infrared sources are identified with optical counterparts. The mid-infrared emission from the bar is offset from optical emission and regions of PAH emission are spatially distinct from the H II region, confirming that the bar is viewed edge-on.

The amount of PAH emission is observed to vary as a function of depth into the PDR at the bar. The region of brightest 8.6, 11.2, and 12.7 $\mu$m PAH emission is located between the edge of the H II region and emission from [C I] observed at infrared wavelengths. At 8.6, 11.2, and 12.7 $\mu$m, PAH emission exhibits a steep rise in intensity close to the H II region and decreases gradually with depth into the PDR. Bright PAH emission is located in regions of high optical depth and low temperature relative to the hotter, more optically thin regions of ionized gas.

A simple model is developed to predict PAH spatial variations in emission. The spatial variation of [Ne II] 12.81 $\mu$m emission is used as input to the model, and it is demonstrated that the [Ne II] 12.81 $\mu$m emission traces the geometry of the PDR at the bar. The models confirm a basic PDR prediction that the UV field is attenuated exponentially by the dusty material in the PDR. Through modeling, the density is constrained to be $9.7 \times 10^4$ cm$^{-3}$ assuming the radiation falls off as $e^{-1.8A_v}$. At position two, the attenuation model did not predict a few of the spatial emission peaks which may be evidence of higher density clumps in the bar.

In the past, the sharp intensity rise exhibited by PAH bands close to the H II region has been suggested as evidence for the destruction of PAHs inside the H II region. The best fit models demonstrate that the sharp rise is primarily a function of the geometry of the bar. We constrain the destruction time scales through modeling by fitting a separation distance between the [Ne II] and PAH emission. Based on the best fitting models, PAHs are destroyed on timescales of less than 1000 years and over a spatial scale of less than 400 AU of the advancing ionization front. Comparisons with NIR studies further suggest that the PAHs in the bar are destroyed on much quicker time scales and over much shorter distances when exposed to radiation greater than 13.6 eV.
According to PAH theory, the transition from ionized to neutral PAHs at PDR surfaces is traceable by the relative strengths of the PAH features. On large and small size scales, the relative strengths of the 8.6, 11.2, and 12.7 \( \mu \)m PAH features at the Orion bar indicate that there is not a simple transition from ionized to neutral PAHs across the PDR. Because the PAH features generally exhibit the same spatial behavior, the carriers of the PAH emission are predominately due to a single family of PAH emitters with small variations in the relative feature strengths attributed to variations in molecular structures, size, and or chemical composition with depth into the PDR.

We would like to thank the staff at the IRTF for assisting the MIRSI team during the inaugural run at the IRTF during which the data for this work was acquired. Funding for this work was provided by Boston University and the NSF Advanced Technologies Instrument Program.

REFERENCES


Kassis, M., 2004, /it Mid-Infrared Observations of Photodissociation Regions and MIRSI (Ann Arbor, MI: UMI)


This preprint was prepared with the AAS \LaTeX macros v5.2.
Fig. 1.— Mosaic of the Orion Nebula at 20.7 μm. The coordinate offsets are relative to the BN/KL object (5:35:14.3 -5:22:23.6 J2000). The intensity scale enhances the contrast of the relatively diffuse emission found at the bar. The image was smoothed over 3x3 pixels. The location of the slit at which spectra were acquired are overlaid on the image (position one: 98″, -164.5″ and position two: 125″, -156.5″).
Fig. 2.— Incomplete mosaic of the Orion nebula at 11 μm. The coordinate offsets are relative to the BN/KL object (5:35:14.3 -5:22:23.6 J2000). The intensity scale enhances the contrast of the relatively diffuse emission found at the bar. The image was smoothed over 3x3 pixels.
Fig. 3.— BN/KL region at 20.7 $\mu$m scaled to enhance the contrast between the fainter and brighter sources. The coordinate offsets are relative to the BN/KL object (5:35:14.3 -5:22:23.6 J2000). The image displayed is a subsection of the mosaic in Figure 1 before smoothing.
Fig. 4.— Grey scale H-alpha emission mapped with HST with overlays of the contoured emission mapped at 20.7 $\mu$m. The contour levels are set at -1.26, -0.26, 0.24, and 0.74 in units of log(Jy). The HST H-alpha image was supplied by Dr. John Bally.
Fig. 5.— Images of the Orion bar taken at the three CVF wavelengths. The coordinate offsets are relative to the BN/KL object. Images were acquired with the CVF with a central wavelength of 10.5 (A), 10.8 (B), and 11.2 (C) μm.
Fig. 6.— Spectra at two locations at the bar. The offsets are relative to the location of the BN/KL object. The rectangles overlaid on the spectrum at position one (a) mark the regions from which intensities were measured and plotted in Figure 7.
Fig. 7.— Spectra from two spatial locations obtained along the slit centered at position one. The two spectra are normalized to the brightest emission feature. The spectrum that exhibits emission from ionized gas was shifted by 1.0. The primary spectral features are labeled.
Fig. 8.— Relative intensities of spectra features observed at position one as a function of distance. A) Relative intensities of spectral features imaged by Walmsley et al. (2000). Images mapping [Fe III], He I, Br γ, O I, H2, and [C I] were provided by Dr. Testi. The dashed lines from 0.04-0.06 pc represent a region where data was not acquired. The intensities of the emission features were normalized and then shifted by 5, 4, 3, 2, and 1 for [Fe III], He I, Brγ, O I, and H2, respectively. B) Relative intensities of spectral features imaged by Tielens et al. (1993). The 3.3 PAH, H2, and CO intensities are shifted by 0, 1, and 2, respectively. Images mapping the spectral features were supplied by Dr. Meixner. C) Relative intensities of the mid-infrared PAH features. Also plotted is the emission from [Ne II]. The intensities are shifted by 1, 2, 3, and 4 for the 12.7, 8.6, 11.2, and [Ne II] features, respectively. The horizontal axis is the projected distance relative to the location of the MIF (see text).
Fig. 9.— Relative intensities of MIR spectra features at position two as a function of distance from the location of the MIF. The PAH features are labeled by the center wavelength. Also plotted is the emission from [Ne II]. The intensities are normalized by the maximum intensity. The intensities are shifted by 1, 2, 3, and 4 for the 12.7, 8.6, 11.2, and [Ne II] features, respectively. The horizontal axis is the projected distance relative to the location of the MIF (see text).
Fig. 10.— Smoothed color temperature map of the bar overlaid with color temperature contours. Contour levels are 100, 120, 140, 160, and 180 K. The coordinate offsets are relative to the BN/KL object. The dashed line represents the approximate location of the bar at 11.7 μm. θ² Ori A is located at 131″, -154″. The two rectangles with RA offsets of 98 and 125 are the locations of the slit used to acquire spectra at position one and two, respectively.
Fig. 11.— Smoothed optical depth map ($\tau_{10,6}$) overlaid with the temperature contours from Figure 10. The coordinate offsets are relative to the BN/KL object. Grey scale intensities of the optical depth are 0.0 (dark) to 0.0045 (bright). The dashed line represents the approximate location of the bar at 11.7 $\mu$m. $\theta^2$ Ori A is located at 131", -154".
Model of the PAH emission for an arbitrary cloud geometry. In the bottom panel, the relative intensity of [Ne II] as a function of distance is simulated using a fourth degree polynomial. In the middle panel a two dimensional model of the PAH intensity is presented. Each horizontal layer in the two dimensional model is the predicted intensity for a measured $dI_{NeII}/dx$. For every $dI_{NeII}/dx$ we assume the emission results from a layer located at a new height. The grayscale intensity in the middle panel is brightest (white) to no emission (dark) from PAHs. The direction in which we view the cloud is parallel to the height axis. By summing the intensity plotted in the middle panel along the line of sight, we predict the observed PAH emission (top panel).
Fig. 13.— The slope in the [Ne II] emission as a function of distance across the bar. The slopes are provided at positions one and two. The dashed line represents the [Ne II] slope after smoothing over 10 instrument pixels.
Fig. 14.— Maps of log(RMS$^2$) in parameter space. The coefficient B is along the horizontal axis and the shift is along the vertical axis. The top four panels refer to the residuals at position one and refer to the fits at 7.7 (a), 8.6 (b), 11.2 (c), and 12.7 (d) μm. The bottom panel (e) displays the minimization at 11.2 microns for position two.
Fig. 15.— Best fitting models to the intensity of the PAH features across the bar at position one. The solid lines are the observed emission from [Ne II] and PAH features at 7.7, 8.6, 11.2, and 12.7 μm. The dashed lines are the predicted relative fluxes matched to the PAH features. The observed emission features and corresponding models are normalized and then shifted by 0, 1, 2, 3, 4 for the 7.7, 12.7, 11.2, 12.7, and [Ne II] 12.8 μm features, respectively.
Fig. 16.— Best fitting models to the intensity of the PAH features across the bar at position two. The solid lines are the observed emission from [Ne II] and PAH features at 8.6 and 11.2 μm. The dashed lines are the predicted relative fluxes matched to the PAH features. The observed emission features and corresponding models are normalized and then shifted by 0, 1, 2 for the 8.6 11.2, and [Ne II] 12.8 μm features, respectively.
Fig. 17.— Ratios of feature strengths plotted as a function of distance. The feature strengths were normalized to the maximum intensity along the spatial dimension of the spectrum before the ratios were calculated. The ratios of the 8.6, 11.2, and 12.7 μm were determined. The 8.6/11.2 and 12.7/11.2 are shifted to avoid confusion. The average of the ratios is represented by the horizontal line passing through each set of points and is drawn to help identify trends in the data.
<table>
<thead>
<tr>
<th>Date</th>
<th>Object</th>
<th>$\lambda$</th>
<th>Exposure Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/31</td>
<td>Orion Nebula$^a$</td>
<td>11.6</td>
<td>17.4</td>
</tr>
<tr>
<td>11/01</td>
<td>Orion Nebula$^a$</td>
<td>20.6</td>
<td>7.8</td>
</tr>
<tr>
<td>11/02</td>
<td>Orion Bar</td>
<td>8.7</td>
<td>4.3</td>
</tr>
<tr>
<td>11/03</td>
<td>Orion Bar</td>
<td>10.5</td>
<td>21.5</td>
</tr>
<tr>
<td>11/03</td>
<td>Orion Bar</td>
<td>10.8</td>
<td>30.1</td>
</tr>
<tr>
<td>11/03</td>
<td>Orion Bar</td>
<td>11.2</td>
<td>21.5</td>
</tr>
<tr>
<td>11/06</td>
<td>Orion Bar</td>
<td>20.6</td>
<td>174</td>
</tr>
<tr>
<td>11/07</td>
<td>Orion Nebula$^a$</td>
<td>20.6</td>
<td>7.8</td>
</tr>
<tr>
<td>11/02</td>
<td>Orion Bar grism</td>
<td></td>
<td>2608.6</td>
</tr>
<tr>
<td>11/03</td>
<td>Orion Bar grism</td>
<td></td>
<td>870</td>
</tr>
</tbody>
</table>

Table 1: Mid-infrared images and spectra acquired at the Orion Nebula.

$^a$Mosaics that contain the emission from the Bar
Table 2: Regions defined as feature and background. Columns two and three present the center wavelength and band width used to measure the flux from the spectral features. Columns four and five present the spectral range over which the background was estimated.

<table>
<thead>
<tr>
<th>Feature</th>
<th>center $\lambda$ ((\mu)m)</th>
<th>width $\lambda$ ((\mu)m)</th>
<th>background short $\lambda$ ((\mu)m)</th>
<th>background long $\lambda$ ((\mu)m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[\text{Ar}III]$ 8.99 (\mu)m</td>
<td>8.99</td>
<td>0.05</td>
<td>8.84-8.91</td>
<td>9.04-9.12</td>
</tr>
<tr>
<td>$[\text{SIV}]$ 10.52 (\mu)m</td>
<td>10.52</td>
<td>0.05</td>
<td>10.37-10.46</td>
<td>10.59-10.67</td>
</tr>
<tr>
<td>$[\text{NeII}]$ 12.81 (\mu)m</td>
<td>12.81</td>
<td>0.07</td>
<td>12.70-12.74</td>
<td>12.90-12.94</td>
</tr>
<tr>
<td>7.7 (\mu)m PAH$^a$</td>
<td>8.05</td>
<td>0.10</td>
<td>---</td>
<td>9.05-9.22</td>
</tr>
<tr>
<td>8.6 (\mu)m PAH</td>
<td>8.60</td>
<td>0.71</td>
<td>8.23-8.24</td>
<td>9.05-9.22</td>
</tr>
<tr>
<td>11.2(\mu)m PAH</td>
<td>11.30</td>
<td>0.80</td>
<td>10.60-10.90</td>
<td>11.70-12.00</td>
</tr>
<tr>
<td>12.7(\mu)m PAH$^b$</td>
<td>12.64</td>
<td>0.72</td>
<td>12.18-12.28</td>
<td>13.00-13.20</td>
</tr>
</tbody>
</table>

$^a$ Only measure the long wavelength wing of the 7.7 \(\mu\)m PAH feature.

$^b$ $[\text{NeII}]$ 12.81 \(\mu\)m flux subtracted
Table 3: Parameter values for the best fitting attenuation model to the spatial variations of PAH emission features.

<table>
<thead>
<tr>
<th>Pos.</th>
<th>$\lambda$</th>
<th>$B$</th>
<th>$s$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\mu$m</td>
<td>pc$^{-1}$</td>
<td>(AU)</td>
</tr>
<tr>
<td>one</td>
<td>7.7</td>
<td>43</td>
<td>360</td>
</tr>
<tr>
<td>one</td>
<td>8.6</td>
<td>96</td>
<td>480</td>
</tr>
<tr>
<td>one</td>
<td>11.2</td>
<td>71</td>
<td>240</td>
</tr>
<tr>
<td>one</td>
<td>12.7</td>
<td>106</td>
<td>480</td>
</tr>
<tr>
<td>two</td>
<td>8.6</td>
<td>80</td>
<td>720</td>
</tr>
<tr>
<td>two</td>
<td>11.2</td>
<td>63</td>
<td>0</td>
</tr>
</tbody>
</table>