SPITZER IRAC COLOR DIAGNOSTICS FOR EXTENDED EMISSION IN STAR-FORMING REGIONS

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ABSTRACT

The infrared data from the Spitzer Space Telescope are an invaluable tool for identifying physical processes in star formation. In this study, we calculate the Infrared Array Camera (IRAC) color space of UV fluorescent H2 and polycyclic aromatic hydrocarbon (PAH) emission in photodissociation regions (PDRs) using the Cloudy code with PAH opacities from Draine & Li. We create a set of color diagnostics that can be applied to study the structure of PDRs and to distinguish between FUV-excited and shock-excited H2 emission. To test this method, we apply these diagnostics to Spitzer IRAC data of NGC 2316. Our analysis of the structure of the PDR is consistent with previous studies of the region. In addition to UV excited emission, we identify shocked gas that may be part of an outflow originating from the cluster.

Key words: infrared: ISM – ISM: individual objects (NGC 2316) – methods: data analysis

Online-only material: color figures

1. INTRODUCTION

The infrared data from the Spitzer Space Telescope have provided invaluable insights in the field of star formation. In addition to emission from young stellar objects (YSOs), non-stellar extended emission is present in the Spitzer images of star-forming regions. Mid-infrared bubbles trace regions of high-mass star formation where bright shells of polycyclic aromatic hydrocarbon (PAH) emission surround areas filled with 24 μm dust emission (Simpson et al. 2012). In other cases, absorption of Galactic background emission reveals infrared dark clouds where star formation is in its earliest stages (Rathborne et al. 2006; Butler & Tan 2009). When protostellar outflows are present, the emission from the associated shocked gas is detected in all four Spitzer Infrared Array Camera (IRAC) bands, primarily due to a multitude of ro-vibrational molecular hydrogen (H2) emission lines (Noriega-Crespo et al. 2004; Velusamy et al. 2014). In IRAC imaging of high-mass star-forming regions, the presence of extended 4.5 μm emission has been used to identify massive embedded YSOs (Cyganowski et al. 2009).

Ybarra & Lada (2009) calculated the IRAC color space for shocked H2 emission excited through H–H2, He–H2, and H2–H2 collisions. They found the location of shocked H2 in [3.6]–[4.5] versus [4.5]–[5.8] color space to be a function of gas temperature and volume density. The calculated color space for high-temperature shocked gas was found to be consistent with the empirical color cut used by Gutermuth et al. (2008) to distinguish between YSOs and shocked emission. Ybarra et al. (2010) included emission from the CO v = 1–0 band in their calculations of the color space of shocked gas. Analysis using this color space can be used to systematically search for outflows and to study their structures and interactions with environments (Ybarra et al. 2010; Giannini et al. 2013).

While H2 emission is a good tracer of shocked gas from outflows, emission from H2 can also arise from UV fluorescence in cold gas (Black & Dalgarno 1976; Black & van Dishoeck 1987). This often occurs in photodissociation regions (PDRs) surrounding young high-mass stars. UV radiation can have an effect on star formation; it can either help disperse the remnant gas, ending the formation of stars in the region, or trigger a subsequent generation of star formation. UV fluorescent H2 emission is due to the absorption of far-ultraviolet (FUV) photons by H2 into its excited electronic states. These excited molecules will either decay into the ground electronic state continuum and dissociate or decay into discrete ro-vibrational levels of the ground electronic state and then cascade through ro-vibrational transitions, giving rise to infrared photons (Black & Dalgarno 1976). The resulting line ratios from the H2 fluorescent emission can often mimic those of shock-heated gas. Within PDRs, small PAH grains also absorb FUV photons and re-emit in the infrared. This PAH emission is often found to be correlated with H2 emission in H2 shells surrounding PDRs (Velusamy & Langer 2008).

Draine & Li (2007) calculated the IRAC fluxes for PAH emission by varying radiation strength and grain size distribution. In this Letter, we extend this analysis to include H2 fluorescent emission. We calculate the IRAC color space for PDR regions considering geometry of the gas cloud and varying the ratio of incident FUV radiation to gas density. We create a set of color diagnostics that can be applied to study the structure of PDRs. Additionally, we find that the color analysis can be used to distinguish between FUV-excited and shock-excited H2 emission. Finally, we apply these diagnostics to Spitzer IRAC data of NGC 2316 as an example of the usefulness of this method.

2. CALCULATIONS

PDR calculations were performed with version 13.02 of Cloudy, last described by Ferland et al. (2013). This code includes a sophisticated model of the H2 molecule described by Shaw et al. (2005). The code self-consistently calculates excitation, formation, dissociation, and ortho–para conversion for H2. The calculations of the ro-vibrational level populations are performed by following the photoexcitation of H2 into excited electronic states and subsequent decay into ground-state ro-vibrational levels. The code includes the ability to use PAH absorption cross sections from Draine & Li (2007). We used the grain size distribution of Weingartner & Draine (2001) from


























































































































































































































































































































































































































































































































































































































































































































































































































































































































































































































3.5 Å to 1 μm. We considered the total C abundance in the log-normal parts of the size distribution to be \( b_i = 5.52 \times 10^{-5} \). The charge state of a PAH grain affects its opacity. Draine & Li (2007) provide cross sections for both neutral grains and charged grains. The current version of the Cloudy code is unable to self-consistently determine the opacity of the grains from their charge state. In order to work around this limitation, we run the code using an iterative process. First, an initial run of the Cloudy code solved the grain ionization–recombination balance equations (van Hoof et al. 2004) considering a fully neutral PAH distribution in order to obtain ionization fraction distributions as a function of grain size and depth into the cloud. Second, the gas cloud is divided into zones where each zone will have its own grain ionization distribution. For each zone, two separate grain size distributions were then created, one for neutral PAHs and one for ionized PAHs. The code is then run again on each zone, where the input radiation of that zone was the output radiation of its preceding zone.

We considered a simple layout and geometry of a gas cloud to investigate the color space. The volume density of the gas was kept constant and the shape of the external FUV radiation field was set to the Draine field (Draine 1978). We ran a grid of models, varying the ratio of incident FUV flux to gas density \((-2.0 \leq \log(G/n_H) \leq 0.5)\) through the range of the gas density, \( n_H = 10^{5} – 10^{7} \text{ cm}^{-3} \). Using obtained emissivities and opacities for each zone, we applied the radiative transfer equation to calculate the spectra at various lines of sight through the gas. We also investigate different gas geometries by placing slabs of constant thickness at various depths of \( A_V = \{0.1, 1.0, 2.0, 3.0, 4.0, 5.0\} \) mag both in front of and behind the incident radiation.

3. COLOR SPACE DIAGNOSTICS

The resulting infrared spectra from our models were converted into IRAC colors using IRAC spectral response and calibration data (Reach et al. 2005; Hora et al. 2008).

3.1. IRAC Color Space for PDRs

There is often degeneracy in the physical parameters of emitting material in color space; thus, the usefulness of the color space analysis in extracting information is restricted to regions in color space that reveal breaks in degeneracy. From our investigation of the calculated IRAC colors, we find that the [3.6]–[4.5] versus [4.5]–[5.8] color space in the region where \( 2.9 < [4.5]–[5.8] < 3.6 \) has minimal degeneracy and is useful as a tool for analysis. We divide this region into three sub-regions. Figure 1 shows the IRAC [3.6]–[4.5] versus [4.5]–[5.8] color–color plot indicating these various regions.

Region 1. This region of color space is defined by a lower limit

\[
[3.6]–[4.5] > 0.15([4.5]–[5.8]) - 0.92
\]

for \( 3.0 < [4.5]–[5.8] < 3.2 \)

\[
[3.6]–[4.5] > 0.35([4.5]–[5.8]) - 1.56
\]

for \( 3.2 < [4.5]–[5.8] < 3.6 \)

and upper limit

\[
[3.6]–[4.5] < 0.27([4.5]–[5.8]) - 1.19
\]

for \( 3.0 < [4.5]–[5.8] < 3.3 \)

\( ^3 \) The FUV flux \( G \) is in units of \( 1.6 \times 10^{-3} \text{ erg cm}^{-2} \text{ s}^{-1} \).

This region of color space is mostly occupied by thin PDRs of thickness \( A_V \sim 0–2 \) mag. The colors from a plane-parallel PDR model would be found in this region of color space.

Region 2. This region of color space is defined by an upper limit of

\[
[3.6]–[4.5] < 0.35([4.5]–[5.8]) - 1.31
\]

for \( 3.0 < [4.5]–[5.8] < 3.6 \).

This region of color space is occupied by two cases of PDRs: (1) a gas cloud of thickness \( A_V \sim 2–4 \) mag in front of the incident FUV source, or (2) a thick gas cloud behind the incident FUV source. For a thick cloud behind the FUV source, material beyond \( A_V > 2 \) mag does not significantly contribute to the total line-of-sight emission. Additionally, the line-of-sight emission will begin to include a contribution from fluorescent H2 lines.

Region 3. This region of color space is defined by an upper limit of

\[
[3.6]–[4.5] < 0.20([4.5]–[5.8]) - 0.72
\]

for \( 3.0 < [4.5]–[5.8] < 3.4 \)

\[
[3.6]–[4.5] < 0.70([4.5]–[5.8]) - 2.42
\]

for \( 3.4 < [4.5]–[5.8] < 3.6 \).

Incident UV source is behind a gas cloud of thickness \( A_V \sim 4–5 \). The increasing [3.6]–[4.5] color is partly due to the increasing contribution of UV fluorescent H2 emission in the line-of-sight spectra.

Another result of our calculation is that the [4.5]–[5.8] color is an approximate indicator of the \( G/n_H \) ratio, where the line of sight intersects the plane of the incident FUV. We fit the

\[
\text{log}(G/n_H) = 0.5
\]

(Region 3 in the figure). For [4.5]–[5.8] vs. [3.6]–[4.5] color–color plot indicating the region occupied by PDRs (PAH grains and UV fluorescent H2). Region 1 of the color–color space is occupied by gas clouds of thickness \( A_V \sim 0–2 \) mag. Region 2 of the color–color space is occupied by either a gas cloud of thickness \( A_V \sim 2–4 \) mag in front of the incident UV source, or a gas cloud (\( A_V > 2 \)) behind the incident UV source. Region 3 indicates a cloud thickness of \( A_V \sim 4–5 \) mag in front of the incident FUV source. The gray region at [4.5]–[5.8] > 3.6 indicates a region of color space with significant degeneracy. (A color version of this figure is available in the online journal.)
following analytic form to this relationship:

\[
\log(G/n_H) = -19.7 + 10.0a - 1.35a^2,
\]

where \( a = [4.5] - [5.8] \) and \( 2.8 < a < 3.8 \). This relationship is due in part to the dependence of the ionization fraction on \( G/n_H \). Larger \( G/n_H \) results in a larger overall ionization fraction of the PAHs and thus the increasing PAH feature (5.270, 5.700, 6.220 \( \mu m \)) emission in the 5.8 \( \mu m \) band relative to the continuum emission in the 4.5 \( \mu m \) band. Our simple model does not take into account PAH destruction from strong FUV fields, which could affect this color relationship. At \( G/n_H \lesssim 0.04 \), \( H_2 \) begins forming due to self-shielding, and thus the 4.5 \( \mu m \) band will also include emission from UV fluorescent \( H_2 \) lines (Hollenbach & Tielens 1999).

Finally, we find that the [4.5]–[5.8] color can be used to probe the phase of the gas (molecular, mixed, or atomic) where the line of sight intersects the plane of the incident FUV. The emission of gas within the \( H_1/H_2 \) transition zone will have a [4.5]–[5.8] color within the range 3.0–3.3. Mostly molecular gas \((n(H_2)/n_H > 0.3)\) will have [4.5]–[5.8] < 3.0 and mostly atomic gas \((n(H_2)/n_H < 0.25)\) will have [4.5]–[5.8] > 3.3 (see Figure 1). Our calculations show that within the \( H_1/H_2 \) transition zone, the contribution of \( H_2 \) ro-vibrational lines to total emission is \( \sim 5\%–10\% \) in the 3.6 \( \mu m \) band and \( \sim 10\%–20\% \) in the 4.5 \( \mu m \) band. Our model did not include the possible freeze out of small PAH molecules in cold molecular gas \((\log(G/n_H) \lesssim -2)\), which would reduce the contribution of \( H_2 \) emission in the IRAC bands.

It should be noted that external foreground extinction can affect the IRAC colors, although this effect is not very strong due to the relative flatness of the MIR extinction curve (Lutz et al. 1996). Application of most MIR extinction laws results in the [4.5]–[5.8] color to be negligibly affected by extinction (Lutz 1999; Indebetouw et al. 2005). The [3.6]–[4.5] color appears to have a stronger dependence on extinction; however, an \( A_V = 10 \) mag extinction only results in an increase in the [3.6]–[4.5] color of \( \sim 0.1 \) (Indebetouw et al. 2005; Chapman et al. 2009). However, due to variations of the MIR extinction law with environment, the effect of extinction on the [3.6]–[4.5] color may be even less (Wang et al. 2013).

### 3.2. Distinguishing between Shocked and UV Fluorescent Molecular Hydrogen

It is often the case that the excitation mechanism for \( H_2 \) emission is unknown, and in some cases is necessary to understand the nature of the emission. For example, the \( H_2 \) emission from externally illuminated structures such as pillars or globules can have a morphology similar to bow shocks from protostellar outflows. We propose the following simple one-color diagnostic that should suffice in most cases of interest where \( H_2 \) has already been detected (e.g., NIR \( H_2 2.12 \mu m \) imaging):

**Shocked:** \([3.6] - [4.5] \geq 0.5\)

**UV Fluorescent:** \([3.6] - [4.5] < 0.5\).

This diagnostic is particularly useful when only data from the first two IRAC channels are available, such as data from the *Spitzer* Warm Mission. For analysis including the 5.8 \( \mu m \) band, the region of color space defined for shocked \( H_2 \) emission is (Ybarra et al. 2010)

\[
[3.6] - [4.5] > -0.24[4.5] - [5.8] + 1.26
\]

![Figure 2. *Spitzer* IRAC [3.6]–[4.5] vs. [4.5]–[5.8] color–color plot showing the location of shocked \( H_2 \) emission in relation to UV excited PDR emission. (A color version of this figure is available in the online journal.)](image)

for \( 0.25 < [4.5] - [5.8] < 1.5 \)

\([3.6] - [4.5] > 0.8[4.5] - [5.8] + 1.0 \)

for \( -0.5 < [4.5] - [5.8] \leq 0.25 \), whereas gas containing UV fluorescent \( H_2 \) will be in the PDR color space defined in Section 3.1. Figure 2 shows a larger color–color map showing the location of shocked \( H_2 \) emission in relation to UV excited PDR emission.

### 3.3. Background Estimation Method

In order to measure the emission in each pixel, it is necessary to model the background. For small-scale structures, such as shocked \( H_2 \) knots against a variable background, a ring filter can be used to effectively model the background (Ybarra & Lada 2009). However, for the analysis of more extended emission, such as that from PDRs, we use a Bayesian intensity estimator developed by Bijaoui (1980). The pixel intensity histogram is modeled with a Gaussian distribution for noise centered near the sky background level and an exponential distribution prior to describe the asymmetry of the histogram due to non-background emission. The model has the following analytic form:

\[
p(I) = \frac{1}{2a} \exp(\sigma^2/2a^2) \exp[-(I - s)/\alpha] \text{erfc} \left( \frac{\alpha}{\sqrt{2}} \right),
\]

where

\[
\alpha = \frac{\sigma}{a} - \frac{(I - s)}{\sigma}.
\]

\( I \) is the measured pixel intensity, \( s \) is the background level, \( \sigma \) is the width of the Gaussian, and \( a \) is the scale parameter of the exponential distribution.\(^4\) We fit the function \( p(I) \) to the intensity histogram to obtain the values \( a, \sigma, \) and \( s \). The Bayesian estimator of the true intensity is

\[
\hat{i} = I - s - \frac{\sigma^2}{a} + \sqrt{\frac{2}{\pi}} \frac{\sigma e^{-a^2/2}}{\text{erfc}(a/\sqrt{2})}.\]

Therefore, for every pixel in the image we are able to estimate the intensity above the background, and subsequently with the

\[^4\text{erfc} \text{ is the complementary error function as defined by } \text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty \exp(-t^2)dt.\]
registered images we are able to calculate the color for each pixel.

4. APPLICATION OF THE METHOD: NGC 2316

The usefulness of any method needs to be tested. We apply this method to archival *Spitzer* IRAC images of NGC 2316 (=Parasan 18 = L1654, \((\alpha, \delta)(J2000) = 6^{h}59^{m}40^{s}, -7^{\circ}46^{\prime}17^{\prime\prime}\)) from the program 3290 (PI: Langer). This region is a site of star formation containing a young (2–3 Myr) embedded cluster with line-of-sight extinction \(\langle AV \rangle = 4.5\) mag at a distance of 1.1 kpc (Teixeira et al. 2004). Within this region exists a PDR generated by the FUV radiation from a ZAMS B3 star (López et al. 1988; Ryder et al. 1998). Figure 3(a) shows a *Spitzer* IRAC three-color image of the cluster. Figure 3(b) shows a map of the results from our color analysis. The color-coded yellow regions indicate pixels whose IRAC colors are consistent with that of shocked \(\text{H}_2\) emission. Blue, dark green, and light green indicate pixels with IRAC colors consistent with PDRs with line-of-sight thicknesses of \(AV \sim 0–2\) mag, 2–4 mag, and 4–5 mag, respectively.

We find the emission around the B3 star to have colors consistent with PDRs with line-of-sight thickness of \(AV > 4\) mag. We are able deduce that this PDR results from an exciting source embedded within the cloud, which is consistent with previous studies of the region (Ryder et al. 1998; Velusamy & Langer 2008). Our analysis is also consistent with the results from the NIR \(\text{H}_2\) study by Ryder et al. (1998). We identify five of the eight \(\text{H}_2\) emission regions in our color analysis (R2 = North Peak, R4 = S Peak, R6 = NW Arc, R7 = W Arc, R8 = P 18 NW). Figure 4 shows a color analysis map with the locations of the five emission regions indicated by solid boxes. Four of these regions (R2, R4, R6, R7) were found by Ryder et al. (1998) to have \(\text{H}_2\) emission excited through UV fluorescence. These four regions are part of the \(\text{H}_2\) shell observed by Velusamy & Langer (2008). Our color analysis of these four regions reveals they have colors consistent with PDR emission from a cloud with thickness \(AV \sim 4–5\) mag. Additionally, those four regions have \([3.6]–[4.5] \sim 3.2–3.3\), corresponding to the \(\text{H}_1/\text{H}_2\) transition zone where \(\text{H}_2\) is expected to strongly emit (Hollenbach & Tielens 1999).
Ryder et al. (1998) found that region R8 has an H$_2$ (1–0)/(2–1) S(1) line ratio consistent with shock excitation and therefore suggest that R8 may be part of an outflow possibly associated with the previously observed CO outflow found in the region (Fukui et al. 1993). Our analysis reveals this region to have IRAC colors consistent with shock-excited H$_2$, therefore confirming the previous result. Northwest of R8, our color analysis reveals more emission that may be shock-excited. This emission has an elongated structure that, along with R8, may be part of an outflow originating from the B3 star or a nearby neighbor. The projected length of this structure is 0.27 pc (51$''$) and the projected distance from the B3 star to the farthest edge is 0.53 pc (99$''$).

5. CONCLUSIONS

We created a set of Spitzer IRAC color diagnostics to study the extended MIR emission observed in star-forming regions. For PDRs, color diagnostics allow one to probe the depth of the region, the phase of the gas, and estimate the ratio of FUV to gas density. Additionally, we show that the color analysis can distinguish between FUV-excited and shock-excited H$_2$ emission. We present a one-color diagnostic that is able to make use of new data from the Spitzer Warm Mission to distinguish the excitation processes. To demonstrate the usefulness of our method, we applied it to Spitzer IRAC observations of NGC 2316 and find our results are consistent with previous studies of the nebula. Additionally, we identify shocked gas that may be part of an outflow originating from the cluster.

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Facility: Spitzer(IRAC)

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