ISO OBSERVATIONS OF THE INTERSTELLAR MEDIUM IN ELLIPTICAL GALAXIES

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ABSTRACT

Three IRAS-detected elliptical galaxies were observed with ISO-LWS and PHT, and two of them were observed with CAM. The mid-IR images of NGC 1155 and NGC 6958 at 7 and 15 μm show extended emission which follows a de Vaucouleurs profile. The ratio of 15/7 μm flux decreases with radius in both galaxies, approaching the values empirically observed for purely stellar systems.

All three galaxies are detected in the [CII](158 μm) line, and NGC 1155 in the [OI] (63 μm) line. The ISO-LWS observations of the [CII] line are more sensitive measures of cool ISM than HI and CO; the only previous detection of cool gas was of HI in NGC 1052. The observed $L_{[CII]}/L_{FIR}$ ratio in ellipticals follows the same trends seen in other (spiral and irregular) galaxies wherein $L_{[CII]}/L_{FIR}$ decreases with increasing $F_\nu(60\mu m)/F_\nu(100\mu m)$. These trends indicate similar local physical conditions in the ISM in spirals and ellipticals.

The UV radiation from old stellar populations is insufficient, by a factor of 2-30, to produce enough photoelectric heating of gas to account for the cooling via the [CII] and [OI] lines. Heating by X-rays is also insufficient in NGC 6958 and NGC 1155. Given the observed variations in the optical-UV colors and the uncertainties in modelling the UV from old stellar populations, we can make a clear case for young stellar populations in NGC 1155.

Key words: Elliptical galaxies; mid-IR; Far-IR spectroscopy, ISM.

1. MID-INFRARED IMAGING

In spiral galaxies the mid-IR emission is dominated by small grains transiently heated to high temperatures and aromatic features of small grains in the ISM. For ellipticals the ISM-to-stellar ratio is generally low so photospheres and circumstellar dust may contribute significantly to the mid-infrared (Knapp, Gunn & Wynn-Williams 1992), although Sauvage & Thuan (1994) have argued that the same IRAS color-color relation (Helou 1986) holds for early and late type galaxies indicating a similar origin from the ISM. CAM imaging at 7 and 15 μm has enough sensitivity and resolution to yield the spatial distribution of the mid-IR emission. The interpretation is complicated by the dependence of mid-IR emission on both dust and heating source distributions.

The mid-IR emission of both NGC 6958 and NGC 1155 is extended in nature and follows de Vaucouleurs radial profile (Figure 1). To gain signal-to-noise in the outer parts of the galaxies we average the emission in annuli after subtracting the background determined at radii greater than 90″. The LW3/LW2 ratio decreases going from the center of the galaxy outwards (Figure 1) approaching a value of 0.5. This is lower than the ratio found in other (i.e. spiral) galaxies in the sample (cf Helou et al. these proceedings). In NGC 1155 the effective radius for the mid-IR emission is intermediate between those of B-band and Hα light (Figure 2), indicating that both ionizing and non-ionizing radiation heat the dust. A similar result was found for the spiral galaxy NGC 6946 (Malhotra et al. 1996).

From the change in the mid-IR color we infer that the dust in the ISM dominates in the inner parts of the galaxies, and the dust associated with stars becomes dominant in the outer parts. The decrease in LW3/LW2 in the outer parts of the galaxy is then due to different proportions of photospheric and ISM contributions, with the photospheres having a lower LW3/LW2 ratio. The LW3/LW2 ratio of 0.3-0.2 is observed in ellipticals devoid of ISM (Madden et al. 1997).

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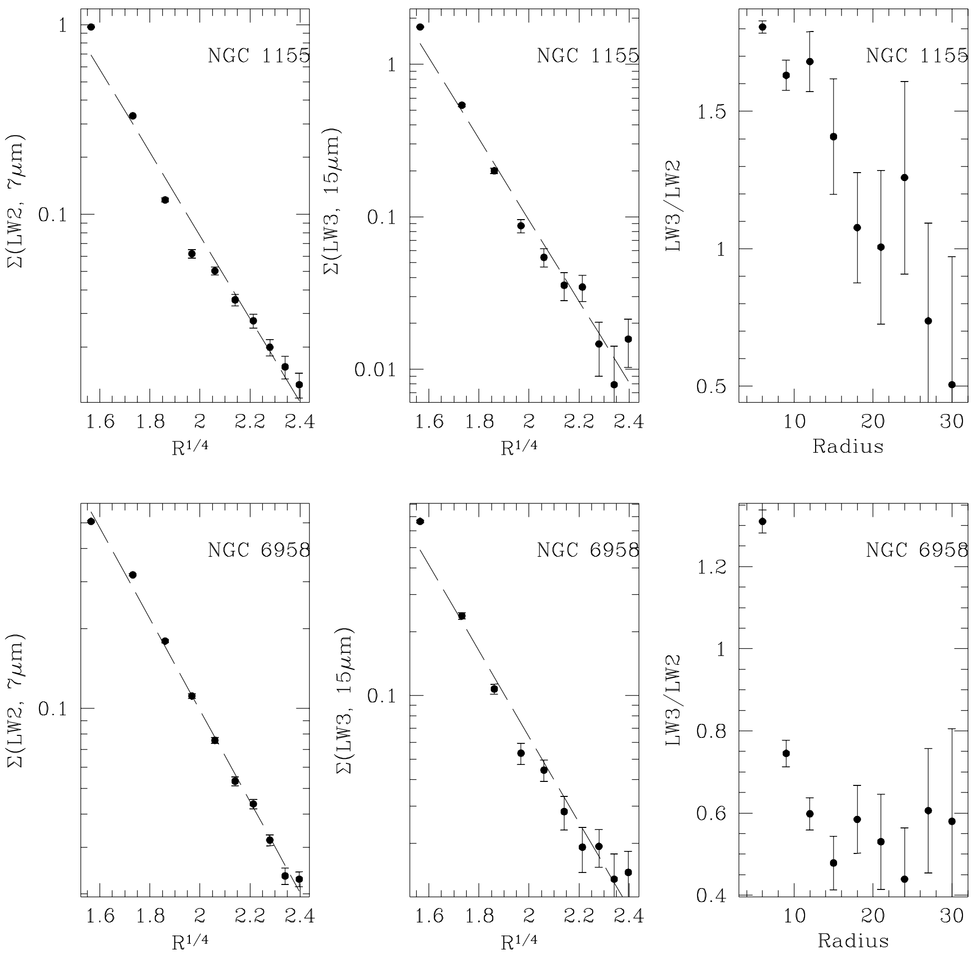

Figure 1. The left and middle panels show surface brightness profiles of NGC 1155 and NGC 6958 at 7 and 15μm respectively. The mid-IR emission follows a de Vaucouleurs radial profile. The right panels show the mid-IR color variation with radius. The ratio of LW3 (15 μm) and LW2 (7 μm) light decreases towards the outer parts of the galaxies, and reaches an asymptotic value of 0.5, characteristic of old stellar populations in galaxies devoid of ISM.

2. FAR-INFRARED SPECTROSCOPY

We detect the [CII](158μm) line in all three galaxies, albeit at low (3σ) S/N for NGC 6958. The other major fine structure cooling line, [OI] (63 μm), is detected in NGC 1155 and undetected in NGC 6958 at uninteresting upper limits. In Table 1 we summarize what is known about the ISM in the three ellipticals: HI (21 cm) is detected in NGC 1052 (van Gorkom et al. 1986) and Hα is detected in all three. [CII] detections imply a minimum mass in H (assuming $T \gg 91$K and $n_H > 10^4 cm^{-3}$) which is 10-100 times smaller than the HI detections and upper limits.

2.1. Trends in line strengths

The 3 elliptical galaxies lie within the broad correlation between $L_{[CII]}/L_{FIR}$ and $F_\nu(60\mu m)/F_\nu(100\mu m)$ (cf. Malhotra et al. 1997 and these proceedings). There is a also a trend of decreasing $L_{[CII]}/L_{FIR}$ with increasing L_{FIR}/L_B. The two ellipticals NGC 6958 and NGC 1052 along with the S0 galaxy NGC 5866 lie at the lowest extreme of L_{FIR}/L_B, indicating a low rate of current star-formation. There is an indication that the $L_{[CII]}/L_{FIR}$ ratio is lower for low values of L_{FIR}/L_B. This is expected in galaxies with low rates of current star-formation since only the UV photons ($\lambda < 2000Å$) contribute to photoelectric heating of gas, while dust is heated by optical as well as UV photons. In early type galaxies which have less active star-formation rate per blue luminosity, we should see a decrease in $L_{[CII]}/L_{FIR}$ and [CII]/CO(1-0).

2.2. Origin of [CII]

With limited knowledge of the phases of the ISM in these galaxies and without assuming Galactic values of temperature and density, it is hard to constrain with what phases of the ISM [CII] is associated. The [CII] emission could be from ionized gas in HII regions, or PDRs (photo dissociation regions) includ-

Table 1. The properties of the ISM in the elliptical galaxies studied in this paper.

Name	Morphology	Distance	M(HI) Mass	$M(H_2)$ in	M(HII) $M_\odot$	$M_H(C^+)$
NGC 1052	E4	14 Mpc	0.7×10^7	$< 3 \times 10^8$	3×10^4	$> 4 \times 10^5$
NGC 6958	E+	28 Mpc	$< 3 \times 10^8$	?	?	$> 8 \times 10^5$
NGC 1155	EL	45 Mpc	?	?	?	$> 1 \times 10^7$

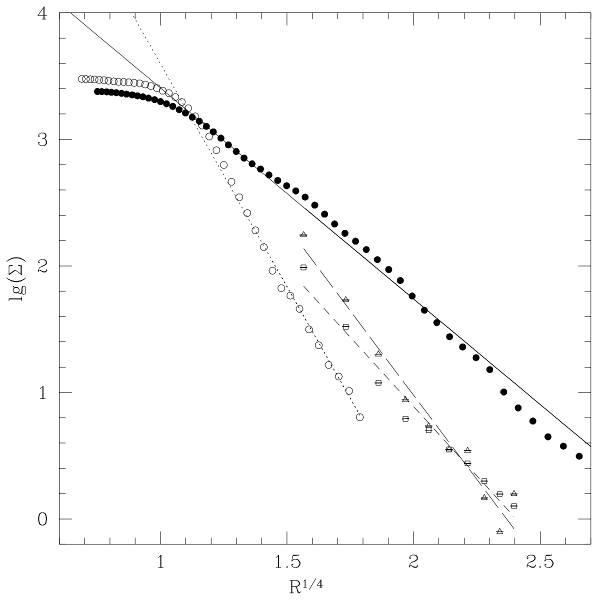

Figure 2. The radial profile in optical B band (filled circles), the Hα (open circles), and the mid-infrared (LW2: open squares, LW3: triangles) in NGC 1155 is plotted along with the best fit de Vaucouleurs profile for each wavelength. The mid-infrared light shows a radial distribution intermediate to the B band and the Hα.

ing neutral atomic medium and UV irradiated surfaces of molecular clouds. Assuming case B recombination ($T = 10^4$ K) and a carbon abundance of $X_C = 3 \times 10^{-4}$ in the HII regions (i.e. solar metallicity with all the C existing as C^+) the upper limit on [CII] emission from HII regions is

$$\frac{L([CII])}{L(H\alpha)} < 0.18 \frac{X_{C^+}}{3 \times 10^{-4}} \left(\frac{1}{1 + n_e/n_{crit}} \right)$$

where n_e is the density of electrons in the HII region and n_{crit} is the critical density for [CII] excitation, which is $84\,cm^{-3}$ for 10^4 K ionized gas. For NGC 1155 and NGC 6958 the observed ratio $L([CII])/L(H\alpha)$ is 2.5 and 58 respectively indicating that most of the [CII] is not associated with HII regions. For NGC 1052 the observed $L([CII])/L(H\alpha) = 0.16$. Taking $n_e = 10^3\,cm^{-3}$, inferred from the ratio of SII lines (Kim 1989) the contribution of HII regions to [CII] emission is still negligible $L([CII])/L(H\alpha) < 0.015$. Thus not a lot of the [CII] emission arises from the HII regions, even if the Hα flux is underestimated by factors of a few due to extinction.

A fair amount of [CII] emission could be from diffuse HI. For a cold neutral medium (CNM) with typical Galactic values T=80K and $n_H = 90\,cm^{-3}$, $M(HI)/L([CII]) = 20\,(3 \times 10^4/X_C^+) M_\odot/\,L_\odot$. For NGC 1052 the observed $M(HI)/L([CII]) = 14$ which can be accommodated with higher gas density or temperature, or some contribution from molecular medium. Comparing the [CII] and [OI] (63μm) line flux measurements of NGC 1155 with PDR models by Kaufman et al. (1999), we infer density $n \simeq 10^2\,cm^{-3}$ and UV radiation density $\simeq 10^2\,G_0$, where G_0 is the UV radiation density in the solar neigborhood.

2.3. Gas energetics

In spirals, [CII] and [OI] are the major coolant of neutral gas and most of the heating is by photoelectrons from dust grains. The potential barrier to photoejection from neutral grains is 6 eV (Bakes & Tielens 1994) or higher, which means that only photons with $\lambda \leq 2000\mathring{A}$ contribute to gas heating. Old stellar populations (PNe, PAGB stars) in ellipticals produce enough ionizing flux to explain the Hα emission seen in the ellipticals (Rose & Tinsley 1974, Binnette et al. 1994). So it is possible that at least some of the photoelectric heating is by old stars.

We use GISSEL (Bruzual and Charlot 1993) stellar population models of instantaneous burst of ages 1 Gyr, 10 Gyr and 13 Gyr to calculate the UV spectra of elliptical galaxies. The mass of each galaxy is normalised to match the B-band flux. The UV heating flux is calculated by assuming that the work function of the grains is 6 eV and the efficiency of overall photoelectric heating process is $\gamma = 0.1$ (Tielens & Hollenbach 1985). The total power that goes into heating the gas is given by:

$$L_{PE} = (\gamma\, f_{abs}\, \int (h\nu - 6eV)\, N_\nu\, d\nu)$$

where N_ν is the number of photons at frequency ν and f_{abs} is the fraction of photons absorbed by the dust. f_{abs} can be estimated from the observed values of L_B/L_{FIR} and using a standard extinction curve with the spectral energy distribution from stellar population models. Table 2 lists the photoionizing luminosity available to heat the gas in old stellar populations, compared to the luminosity of the [CII] and [OI] lines; for NGC 1052 and NGC 6958 the [OI] line strength is estimated using the correlation between [OI]/[CII] and $F_\nu(60\mu m)/F_\nu(100\mu m)$ (Malhotra et al. these proceedings).

The UV heating produced by the old stellar populations fails to account for the [CII] and [OI] emission by factors of 2 or 3 in NGC 1052, NGC 6958 and clearly fails for NGC 1155 by a factor of 30. The theoretical estimates of UV production by old

Table 2. Photoionization luminosity vx luminosity of the [CII] and [OI] lines.

Name	L([CII])	L([OI]) (Luminosity	L(CII+OI) in	L(Hα) $L_\odot$)	L_{PE}(1 Gyr)	L_{PE}(10 Gyr)	L_{PE}(13 Gyr)
NGC 1052	0.5×10^6	(0.25×10^6)	0.75×10^6	3.2×10^6	0.1×10^6	0.06×10^6	0.2×10^6
NGC 6958	1.6×10^6	(0.66×10^6)	2.3×10^6	2.5×10^4	0.4×10^6	0.3×10^6	0.9×10^6
NGC 1155	20×10^6	20×10^6	40×10^6	8.1×10^6	0.8×10^6	0.5×10^6	1.7×10^6

populations are uncertain and vary significantly with age and metallicity (cf. Magris and Bruzual 1993). The observed optical-UV colors (1550-V) of ellipticals vary by a factor of 10 for active and quiescent galaxies (Burstein et al. 1988). IUE spectra, between 1250 and 1850 Å, exist only for NGC 1052 (Burstein et al. 1988). Extrapolating the IUE spectrum to 912 Å and estimating from the FIR/Blue colors that $f_{abs} = 0.04$, we recalculate that $L_{PE} = 0.07 \times 10^6 M_\odot$, about a tenth of the UV luminosity implied by [CII] and [OI] observations. The extra UV could come from very obscured source(s).

These sources could be young stars or X-rays from hot gas and active nuclei. Both the x-ray luminosity and temperature of NGC 1052 indicate that the x-ray emission is dominated by the seyfert nucleus (Davis and White 1996). The X-ray luminosity of NGC 1052 is $\simeq 3 \times 10^6 L_\odot$ of which about 10% could be used up for heating in atomic medium and about 40% in molecular medium in the low ionization case (Maloney et al. 1996). But in XDRs one expects a higher line to continuum ratio as the X-rays are equally efficient at heating the gas and the dust, whereas the UV radiation in PDRs heats dust much more efficiently. Because NGC 1052 follows similar trends in $L_{[CII]}/L_{FIR}$ as the other (spiral) galaxies in the sample, significant X-ray heating of gas is not a favored scenario. NGC 1155 and NGC 6958 were not detected by Einstein or ROSAT. We estimate the X-ray luminosity from the $L_X - L_B$ relation (Fabbiano et al. 1992) to be $\simeq 10^5 L_\odot$ and $\simeq 0.7 \times 10^5 L_\odot$ for NGC 6958 and NGC 1155 respectively. That is simply not sufficient to heat the gas to produce the [CII] flux seen (Table 2).

3. SUMMARY

(1) The Mid-IR emission from elliptical galaxies arises both from ISM and stars. 7/15 μm ratio varies with radius indicating that ISM dominates at the centers. In NGC 1155 the dust emission extends to 10 kpc.

(2) [CII] (158 μm) and [OI] (63 μm) lines are detected in galaxies where HI and CO detections were difficult, making ISO-LWS one of the two most sensitive probes of small quantities of warm ISM. Hα was detected in all. [CII] does not arise in classical HII regions, and is associated with HI in NGC 1052.

(3) The fluxes in the cooling lines, [CII] and [OI], provide fairly stringent lower limits on the UV flux between 912 and 2100Å. With all the uncertainties in modelling, UV from evolved stellar populations is insufficient by at least a factor of 2-3 for NGC 1052 and NGC 6958 and a clear factor of 30 for NGC 1155. In NGC 1155 and NGC 6958 X-ray gas heating is also insufficient.

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