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Letter to the Editor: first results from ISO

ISM parameters in the normal galaxy NGC 5713*

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Abstract. We report ISO Long Wavelength Spectrometer (LWS) observations of the Sbc galaxy NGC 5713. We have obtained strong detections of the fine-structure forbidden transitions [C II] 158 μm, [O I] 63 μm, and [O III] 88 μm, and significant upper limits for [N II] 122 μm, [O III] 52 μm, and [N III] 57 μm, and have measured the galaxy's FIR dust continuum. These observations represent the first FIR line survey of a nearly normal galaxy and allow us to make comparisons with COBE results for the Milky Way, and with KAO observations of IR-bright starburst galaxies. We find that NGC 5713 displays a fairly high [C II]/FIR ratio ($\sim 0.7\%$). Under the assumption that the disk emission is dominated by photodissociated molecular gas, we model the FIR continuum and the [C II] and [O I] line fluxes to derive the density of the warm atomic gas surrounding molecular clouds and the UV flux incident on the clouds. In this model, we find higher densities and lower UV fluxes in NGC 5713 than are typical for starburst galaxies, but higher UV fluxes than suggested for the disks of NGC 6946 and the Milky Way. We also discuss alternative origins for the strong [C II] emission, such as from a diffuse component of cold H I .

Key words: Galaxies: individual - NGC 5713; Galaxies: ISM; Galaxies: starburst; Infrared: galaxies

1. Introduction

We report the first spectroscopic observations from the Infrared Space Observatory (ISO; Kessler et al. 1996) under the US Guaranteed Time project on the interstellar medium of star-forming galaxies (Helou et al. 1996). We have used the ISO LWS (Clegg et al. 1996) to measure the flux in six transitions from NGC 5713, one of approximately sixty galaxies in the project. These LWS results are the first FIR observations of the global emission in C, N, and O transitions from a nearly normal galaxy.

NGC 5713 is an Sbc(s)pec galaxy at a redshift of 1883 km s^{-1}, implying a distance of 24 Mpc for H_0=75 km s^{-1} Mpc^{-1} (assumed hereafter). It has multiple spiral arms which originate near the center and maintain high surface brightness for about 1/2 revolution out to 30″. Beyond this radius, there is only a single smooth and continuous arm of low surface brightness, earning this system its "pec" morphological label. IRAS observations indicate the FWHM of the 25 and 60 μm emission is about 25″ while the optical disk extends to 120″ in diameter. Active star formation is indicated by H II regions situated on the inner arm fragments. With its intermediate values of FIR luminosity, $L_{\rm FIR} = 2\times10^{10}$ $L_\odot$, and infrared-to-blue luminosity ratio of $\sim$2, this galaxy is relatively

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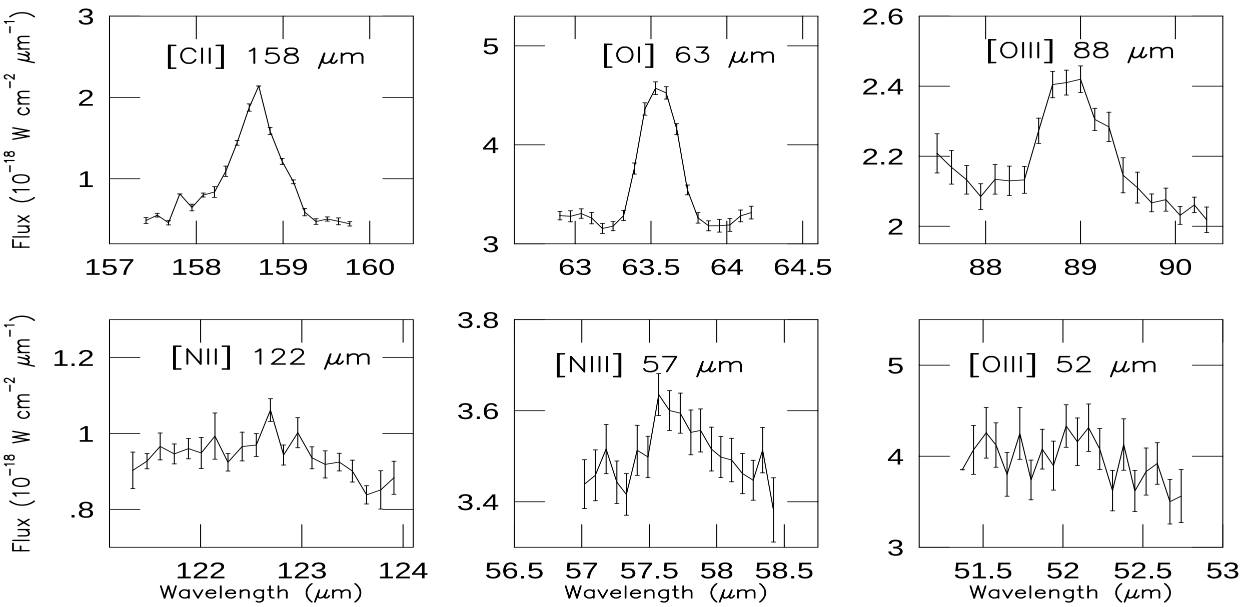

Fig. 1. NGC 5713 LWS atomic fine structure lines

active in star formation, though not an extreme "starburst" system. Although it is part of a small cluster of predominantly late-type spirals, NGC 5713 is located at a projected distance of 60 kpc from its closest neighbor and possesses a fairly low FIR to molecular emission ratio, $L_{FIR}/L_{CO} < 25$, characteristic of an isolated spiral (Tinney et al. 1990).

2. Observation and Analysis

NGC 5713 was observed during ISO's Performance Verification period using the LWS grating line-mode AOT, LWS02, with the 80″ beam of the LWS encompassing the entire infrared bright central disk. Each of the six lines was observed for a time between 6 and 100 seconds per spectral element (see Figure 1), with $\lambda/\Delta\lambda \sim 200$, and the detected lines appeared at the expected wavelengths, adjusted for the galaxy's redshift. Flux calibration included the application of in-orbit detector responsivity values modeled as a function of time. Post-pipeline processing was accomplished with the ISO Spectral Analysis Package, ISAP, specifically using the Rutherford Appleton Laboratory's Graphic User Interface (RAL GUI) designed for the purpose. About 90% of the data were determined to be free of detector gain drifts due to cosmic ray hits, and were retained in the reduction. Mean values and standard deviations were computed at each wavelength and line fluxes were determined by direct integration of the profiles. Upper limits for the non-detections are 3 times the rms noise level taken over the detector resolution element. In the [N III] 57 μm observation, the feature in evidence stands at about 3.4 σ. We consider this detection to be tentative at best, and use the flux estimate in some analysis below so as to gauge its possible implications.

The ISO LWS continuum flux densities deviate substantially from the spectrum expected for NGC 5713 from the IRAS data assuming a superposition of blackbody components (Table 1). They are ~2 times too high at short wavelengths. This disagreement may be due to mis-calibration of the ISO data, either because of overestimated detector responsivities or under-estimated dark currents. In the first case the line fluxes would suffer the same overestimation as the continuum, whereas in the second they would be more accurate than the continuum. In the absence of conclusive evidence as to its cause, this disagreement was used to bound the measurement uncertainty by considering three possibilities: (1) all LWS data are correct as reduced; (2) both continuum and line fluxes from LWS have to be scaled so the continuum agrees with the IRAS-based estimates; and (3) LWS line fluxes are correct, but the continuum is given by the IRAS estimates. The three sets of values were carried through the subsequent analysis, and yielded the ranges plotted in Fig. 2, 3 and 4. The statistical errors for the line fluxes of the detected lines were relatively small: less than 5% for the three detections.

3. Atomic, Molecular, and Ionized Gas

The detected line fluxes (Table 1) are within the general range observed by the Kuiper Airborne Observatory (KAO) in active star-forming galaxies (Figures 2–

Table 1. NGC 5713 Results from LWS Observations

Species	λ_0 (μm)	Line Flux (10^{-19} W/cm^2)	Continuum[a] (LWS; Jy)	(IRAS; Jy)
[O III]	51.8	<5.6	36	14
[N III]	57.3	<1.0	37	17
[O I]	63.2	3.1	43	20
[O III]	88.4	2.4	54	32
[N II]	121.9	<1.5	44	43
[C II]	157.7	8.3	49	39

[a] The observed ISO/LWS continuum flux density and the predicted continuum flux density based on IRAS measurements.

4). The [O I] and [C II] fluxes in NGC 5713 are several parts per thousand of the FIR continuum, and the line-to-continuum ratios for the three detected lines are within a factor of three of the values observed in M82 (Lord et al. 1996a). The FIR continuum here is defined as the emission between 42.5 and 122.5 μm (Helou et al 1988). In comparison to the KAO background-limited instruments, observations with the ISO LWS are 5–10 times more sensitive, particularly between 51 and 88 μm.

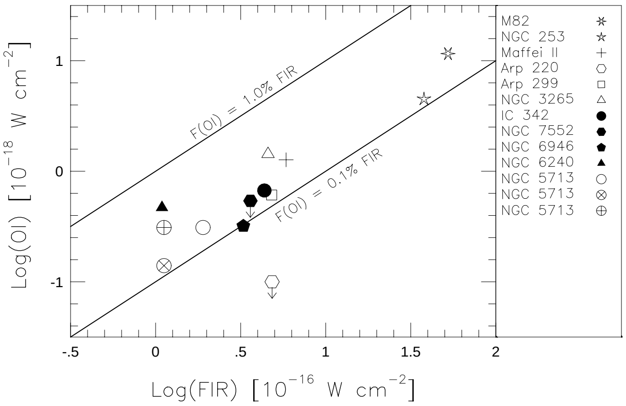

Fig. 2. ISO/LWS NGC 5713 results compared with KAO sample of IR-bright galaxies (Lord et al. 1996b) showing [O I] 63 μm vs. FIR continuum. The IR-bright sample shown were observed using 45–60″ apertures which for most of the sources encompassed their central 0.5–3 kpc. Exceptions to this were the most distant sources: NGC 6240; NGC 3256; Arp 220; and Arp 299, which fell largely or completely within the apertures. The three data points shown for NGC 5713 correspond to the three cases discussed in §2, ○ for case (1); ⊗ for case (2); and ⊕ for case (3).

In NGC 5713, the ([C II]+[O I])/FIR ratio is high, between 0.9 and 1.0%, with the line contribution dominated by the [C II] flux: [C II]/FIR $\sim$ 0.7%. Assuming that the [C II] emission in NGC 5713 originates primarily from photodissociation regions (PDRs), we use standard models

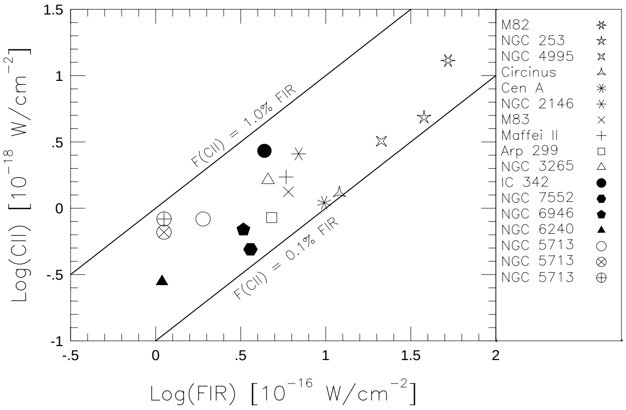

Fig. 3. [C II] 158 μm vs. FIR continuum. See Fig. 2 caption.

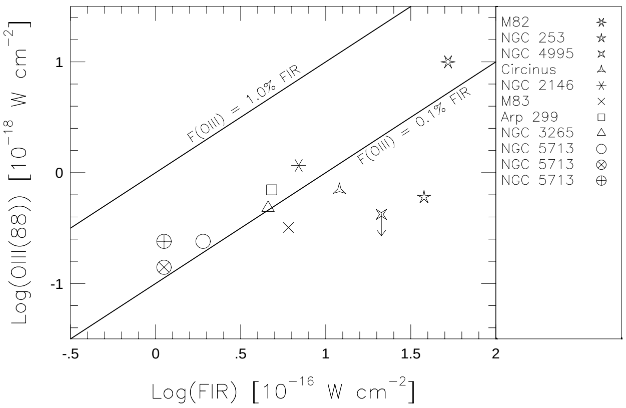

Fig. 4. [O III] 88 μm vs. FIR continuum. See Fig. 2 caption.

(Wolfire, Tielens, & Hollenbach 1990, hereafter WTH; and Tielens & Hollenbach 1985) to interpret the [O I] and [C II] line fluxes. The line and continuum measurements indicate a relatively high ratio n/G_0, where n is the atomic gas density in cm^{-3} and G_0 is the UV radiation field strength normalized to its value in the local neighborhood of the Milky Way. The FIR line to continuum ratio measured in the starburst galaxies shown in Figure 2 range from 0.2 to 0.7%, with a median value of 0.5%, and a corresponding ratio n/G_0 = 15. For NGC 5713 we deduce n/G_0 = 50. The [C II]/[O I] ratio in NGC 5713 is between 3 and 5, distinctly higher than in starburst systems where it is typically close to 1.0 (Lord et al. 1996b). Thus for NGC 5713, the atomic line ratio and the line to continuum ratio are consistent with regions of high atomic gas density, log(n) $\sim$ 4.2 and relatively low UV illumination, log(G_0) $\sim$ 2.8.

Physical parameters based on PDR models are uncertain to the extent that media other than PDRs contribute to the emission from the galaxy, especially ionized gas (H II regions and warm diffuse gas), and cold neutral (H I) gas. Comparing the NGC 5713 results to COBE measurements of the Milky Way, the global [C II]/[N II](122 μm) flux ratio in both sources is large; for the Milky Way the ratio is 20 (Bennett et al. 1994) and for NGC 5713 the ratio is > 5.

These high ratios preclude the possibility of an extremely low density component ($n < 0.1$ cm^{-3}) being present and responsible for the [C II] emission (c.f., Bennett et al.). Also, from H II region models, the [C II] contribution from classical H II regions is very limited.

In the only other published FIR spectroscopy study of a relatively quiescent disk galaxy, Madden et al. (1993) present a complete [C II] map of NGC 6946, find a high [C II]/FIR ratio (1.3%, adjusted to the definition of FIR above), and conclude that over half of the disk [C II] emission is associated with an extended cold H I component and not dense PDRs. However, the regions for which the H I contribution was considered important were located outside the galaxy's optical and Hα disk, and regions located in the large gaps in the galaxy's loosely wrapped outer arms. In contrast, NGC 5713's optical and Hα disk shows a more tightly wrapped pattern that fills the ISO LWS beam and displays an average FIR surface brightness which is a factor of 10 greater than in the extended regions of NGC 6946 (980 $L_\odot$/pc^2 vs. 90 $L_\odot$/pc^2). We argue that it is unlikely that the fluxes from NGC 5713 are dominated by a cold H I component: if a major portion of the disk consisted of cold neutral gas, then the high FIR surface brightness region of this galaxy would have to be confined to a very small area, contrary to the extended distributions observed by IRAS and in Hα.

In the Milky Way, the global [C II]/FIR ratio is ~ 0.9 (Wright et al. 1990, adjusted to the definition of FIR used above); significantly higher than in NGC 5713. Bennett et al. found, as in NGC 6946, that in the inner few kpcs of the Milky Way disk, the [C II] emission is associated with the molecular gas (the molecular ring), but in the outer disk it seems to be uncorrelated with discrete sources and of a diffuse nature. The authors conclude that in the outer Milky Way, the [C II] emission originates mostly in cold H I clouds, with a possible molecular gas PDR contribution. In the inner galaxy, in the vicinity of the molecular ring, the [C II]/FIR emission maintains the constant value of 0.9. The fact that this ratio is lower in NGC 5713 than in the Milky Way suggests, in the context of PDR models, a stronger UV illumination of the molecular surfaces in NGC 5713, and generally more star formation activity. This conclusion is in keeping with NGC 5713's relatively strong FIR surface brightness. Since the disk of NGC 5713 is rich in molecular gas ($M(H_2) = 9.4 \times 10^9$ $M_\odot$, Tinney et al. 1990) and has a high FIR surface brightness, the PDR interpretation of the [C II] emission is favored.

We have also modeled the ionized component of the ISM in NGC 5713 using the H II region modeling code of Rubin et al. (1994). By comparing emission lines of the same element, we determine the electron density, n_e, in these regions and the effective temperature, $T_{\rm eff}$, of the ionizing stars, and do so independently of any elemental abundance assumptions. The lower limit on the [O III] 88 μm/[O III] 52 μm flux ratio of 0.43 constrains the typical H II region electron density to $n_e < 10^3$ cm^{-3}, which is within the expected range for normal H II regions. Taking the [N III] 57 μm result as a tentative 3.4 σ detection, we find a lower limit to the line flux ratio, [N III]/[N II] > 0.67. Multiplying this ratio by the volume emissivity ratio $\epsilon_{122}/\epsilon_{57}$, assuming the H II regions have densities in the range between 10^2 and 10^3 cm^{-3}, gives a lower limit for the stellar effective temperature in a range between 33,500 and 35,000 K. These lower limits are consistent with the findings of Doherty et al. (1995) for NGC 5713, who use their measured value of the He I (2.058 μm)/Brγ ratio of 0.32 for this galaxy to constrain the typical $T_{\rm eff}$. Depending on the primordial helium abundance and H II region electron temperature assumed, they find a $T_{\rm eff}$ range between 35,000 and 37,500 K for NGC 5713.

Future work in our Normal Galaxies Project includes the imaging of NGC 5713 (and other sample members) using ISOCAM to determine, with higher resolution, the location of the FIR emissive regions and also radio mapping in CO isotopes and H I to probe the gas content of the ISM.

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