[C II] 158 μm OBSERVATIONS OF A SAMPLE OF LATE-TYPE GALAXIES FROM THE VIRGO CLUSTER*

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ABSTRACT

We have observed 19 Virgo cluster spiral galaxies with the Long Wavelength Spectrometer (LWS) onboard ESAs Infrared Space Observatory (ISO) obtaining spectra around the [C II] 157.741 μm fine structure line. These 19 galaxies are relatively quiescent in star forming activity compared to previous studies from airborne observatories.

Fifteen of the nineteen galaxies were detected in the [C II] line. Any influence of the Virgo cluster environment on the [C II] emission was found to be small compared with the strong dependence of the line emission on basic measurables such as morphology. These relatively quiescent galaxies exhibit a smaller range of [CII] to FIR ratios compared to other galaxy surveys, yet there is a good correlation between the strength of the [C II] line and the Far-IR flux, as measured by IRAS.

Key words: Galaxies: clusters: general; Galaxies: general; Galaxies: ISM; Infrared: galaxies

1. INTRODUCTION

The ISO (Kessler *et al.* 1996) Guaranteed Time programme VIRGO, Völk *et al.* in prep, is a study of a complete volume-limited, unbiased sample of spiral, irregular and BCD galaxies from the Virgo cluster, selected from the Virgo Cluster Catalogue (VCC) of Binggeli *et al.* 1985, as described in Boselli *et al.* 1997. While the VIRGO proposal is primarily photometric, we wished to observe many of these galaxies spectroscopically. Various constraints limited observations to the [C II] 157.741 μm cooling line. This line should probe photodissociation regions (cf. Stacey *et al.* 1991) associated with massive star formation, and also the diffuse components of the Interstellar Medium (e.g. Nakagawa *et al.* 1998). It fact, it has been observed not only in "compact" regions of the Galaxy like HII regions, OB associations, reflection nebulae, and planetary nebulae, but also in "diffuse" regions, as well as for entire galaxies. [C II] emission is thought to be the most important gas cooling process in late type galaxies, balancing the photoelectric heating from grains.

In field galaxies the [C II] line has a luminosity of the order of 10^{-3} to 10^{-2} that of the total FIR flux of a galaxy (e.g. Malhotra *et al.* 1997). The present sample, selected from the Virgo cluster, better represents the properties of the [C II]-line emission in galaxies less active in star-forming activity (even at the top end of the luminosity range observed) than the sample of Malhotra *et al.* 1997.

At the distance of the Virgo cluster (taken to be 21 Mpc), the 80 arcsec beam of LWS, Clegg *et al.* 1996, covers and area of approximately 7 kpc in diameter – optical images of the Virgo galaxies by Sandage, Binggeli & Tammann 1985 indicate that the LWS beam covers out to the observed spiral arms. The extended [C II] emission detected at this distance in NGC 6946 by Madden *et al.* 1993 accounted for 70% of the total [C II] emission. Observation of Virgo galaxies with LWS therefore detects not only [C II] emission from the dense nucleus but, assuming Virgo galaxies are similar to NGC 6946, will primarily sample the [C II] emission from diffuse regions in and between the spiral arms.

This paper presents a preliminary reduction, analysis and discussion of the [C II] data. The full data will be presented in Leech *et al.* in prep. A companion paper at this conference (Pierini *et al.* this conference), extended in Pierini *et al.* 1999, discusses the [C II]-line emission in more detail and its relation to other measures of the star-forming activity.

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Table 1. Sample galaxies and positions of selected reference fields.

Target	Alternate name	RA (J2000)	DEC (J2000)	Core or Periphery	60 μm flux (Jy)	100 μm flux (Jy)	B_T
VCC 66	NGC 4178	12 12 46.9	10 52 07.0	P	2.8	9.0	11.9
VCC 92	NGC 4192,M98	12 13 48.4	14 54 07.2	P	6.5	21.5	10.9
VCC 460	NGC 4293	12 21 13.2	18 23 03.6	P	4.6	10.6	11.2
VCC 857	NGC 4394	12 25 56.0	18 12 47.6	P	1.0	4.3	11.8
VCC 873	NGC 4402	12 26 06.8	13 06 47.6	C	5.4	17.4	12.6
VCC 1003	NGC 4429	12 27 26.2	11 06 30.3	C	1.4	4.3	11.1
VCC 1043	NGC 4438	12 27 45.7	13 00 30.4	C	3.7	13.1	10.9
VCC 1110	NGC 4450	12 28 29.5	17 05 06.8	P	1.4	7.6	10.9
VCC 1158	NGC 4461	12 29 03.0	13 11 07.1	C	<0.2	<0.8	12.1
VCC 1253	NGC 4477	12 30 02.9	13 38 07.7	C	0.5	1.0	11.3
VCC 1326	NGC 4491	12 30 57.2	11 29 02.1	C	2.8	3.3	13.4
VCC 1412	NGC 4503	12 32 05.5	11 10 38.8	C	<0.2	1.0	12.1
VCC 1690	NGC 4569,M90	12 36 49.9	13 09 53.8	C	8.8	25.0	10.2
VCC 1727	NGC 4579	12 37 43.5	11 49 06.4	C	4.9	19.6	10.6
VCC 1813	NGC 4596	12 39 56.3	10 10 38.0	P	0.4	1.0	11.5
VCC 1869	NGC 4608	12 41 13.6	10 09 14.9	P	<0.2	<0.5	12.0
VCC 1972	NGC 4647	12 43 32.4	11 34 46.7	P	4.9	15.9	12.0
VCC 1987	NGC 4654	12 43 57.2	13 07 35.1	P	13.4	33.4	11.1
VCC 2070	NGC 4698	12 48 23.2	8 29 14.9	P	<0.2	1.6	11.5
VBACK01		12 13 30.9	15 30 47.2				
VBACK03		12 13 52.4	8 29 12.2				
VBACK04		12 25 05.9	17 43 52.1				
VBACK12_1		12 43 08.5	9 47 34.4				
VBACK12_2		12 43 08.5	9 47 34.4				
VBACK13		12 48 14.5	12 58 38.7				

2. SAMPLE SELECTION AND OBSERVATIONS

The galaxies observed in the [C II] 158 μm line are a subsample of a large complete sample of late-type galaxies selected from the Virgo Cluster catalogue of Binggeli et al (1985) for observations with the ISOPHOT (Lemke *et al.* 1996) and ISOCAM (Cesarsky *et al.* 1996) instruments. The parent sample, which is defined in Völk *et al.* in prep (see also Boselli *et al.* 1997), was selected from a cluster as this represented the most convenient way of ensuring completeness in a wide variety of intrinsic properties, embracing a large dynamic range in star-formation activity. We chose Virgo cluster member galaxies because of the high level of completeness of the VCC, (to B_T 18), because at the distance to the cluster the typical angular sizes of the IR emitting regions are well matched to the angular resolution of ISO, the distance of this cluster was optimum for the detection of dwarf galaxies with ISOPHOT and because galaxies in the peripheral regions are thought to be freshly infalling from the field (Tully & Shaya 1984) and therefore less representative of the cluster environment. In order to provide a statistical check of the influence of the cluster environment on the far-infrared properties, the selection was made from two contrasting regions, i.e. cluster core and cluster periphery.

LWS was capable of detecting a large fraction of the spiral galaxies in the parent sample (based on predictions from the IRAS fluxes and the average [C II]-line to FIR continuum ratios of late-type galaxies observed with KAO), but constraints on the available observing time restricted us to a sample of 21 spirals earlier than Scd and complete to B_T=12.3 mag. Of these 21 targets, the interacting pair VCC1673 – 1676 was not included because the LWS beamwidth was not able to separate the individual emissions and VCC 836 was not observed due to conflicts with another programme. These final 18 giant Virgo spirals nevertheless provide a sample of relative quiescent galaxies in comparison to other samples of normal spiral galaxies selected for ISO observations (i.e. Malhotra *et al.* 1997).

One other optically faint core galaxy, VCC 1326, was observed to serve as a cross-calibration target between the LWS measurements and the ISOPHOT measurements of the larger VIRGO programme.

Information on all these galaxies is given in Table 1, together with the positions of sky background reference fields (denoted VBACK in the following tables and figures) to check for foreground [C II] emission from the Milky Way.

The observing log was given in Leech *et al.* 1998. All observations carried out were standard grating range scans (AOT 2's), and sets of observations were used to observe several galaxies in sequence (in ISO terminology, the observations were concatenated), with one sky background position used for each set.

3. DATA REDUCTION AND RESULTS

The Auto Analysis Results from Off-Line Processing (OLP) version 6 were processed further using the ISO Spectral Analysis Package (ISAP) by: reading data in; discarding bad LWS data points; averaging scans for detector 8 (the one covering the 158 μm region); and finally fitting continua and gaussians to

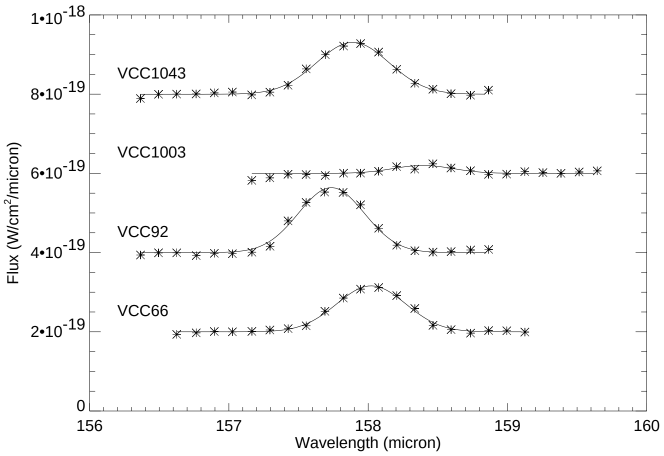

Figure 1. Example Virgo galaxy observations. The level of the baselines is arbitrary.

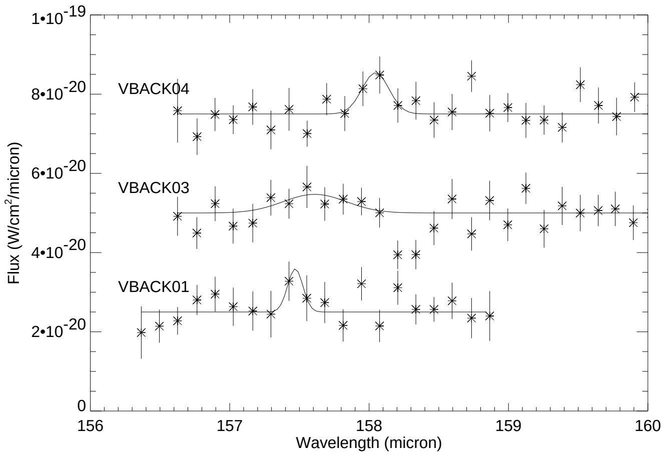

Figure 2. Example Background observations. The level of the baselines is arbitrary.

any lines seen in the data to obtain flux and central wavelength.

Of the 19 galaxies observed, 15 were detected. Of the six background positions used, five had no detectable emission at galactic [C II] wavelengths and one was repointed to VCC 873 (confirming the line flux and wavelength for that galaxy). In several galaxy observations (e.g. VCC 1110) galactic [C II] emission was observed, and in all such cases was measured and noted. In only one case do we think there may be confusion between emission from galactic [C II] and the target Virgo galaxy (VCC 1326).

Example [C II] line wavelength regions are shown in figure 1, and example background positions are shown in figure 2. In cases where no line was present the strongest feature in the spectral region was taken to be the upper limit of detectability. A few of the observations suffer from memory effects and/or glitches that cause the first few short-wavelength datapoints to be systematically lower than the continuum. These points were not used when deriving the line or continuum fluxes.

Line fluxes, central wavelengths and continuum fluxes will be presented in Leech *et al.* in prep.

4. DISCUSSION

Figure 3 shows the relation between the [C II] flux and the FIR flux from IRAS measurements given by $FIR = 1.26 \times 10^{-18}\ (2.58 \times F_\nu(60\mu m) + F_\nu(100\mu m))\ Wcm^{-2}$ (Helou *et al.* 1988). Despite the spatial mis-match between the LWS 80 arcsec diameter circular aperture and the larger IRAS square apertures, there is a good correlation between these observed quantities despite the approximately two orders of magnitude range in both observable quantities.

This correlation is consistent with the LWS [C II] measurements in 5 Sc or later Virgo spirals by Smith & Madden 1997. Galaxies which have higher continuum and line brightnesses tend to have later Hubble

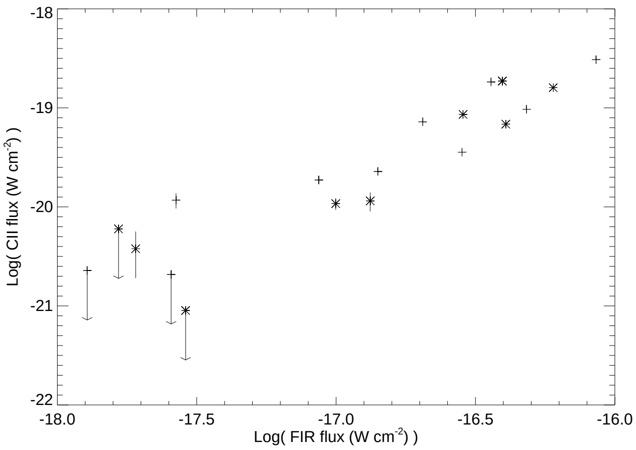

Figure 3. [C II] flux against FIR flux. Error bars are marked in the vertical, where they are larger than the symbol size, and upper limits are marked. Core galaxies are marked by '*', periphery by '+'.

types, consistent with the increase in star formation activity with increasing lateness, e.g. Kennicutt *et al.* 1994. The tendency for the correlation to flatten off with increasing brightness, as observed by Stacey *et al.* 1991 for a sample embracing starburst and ultraluminous galaxies, is not apparent for the relatively quiescent Virgo sample.

The range of the [C II] to the total IRAS FIR flux ratio is from 0.1% to 0.5%. It covers the ranges expected for compact sources (0.2%), such as active star-forming regions, to the diffuse component of the ISM (0.6%), Nakagawa *et al.* 1998. Galaxies observed by Stacey *et al.* 1991 cover the range 0.15 – 0.6%, and in NGC 5713 the ratio is 0.7% (Lord *et al.* 1996).

The [C II]/FIR ratio increases with the current star formation rate (measured by the Hα EW) in quiescent galaxies till a "plateau" value, typical of gas-rich and starburst galaxies – see Pierini et al. this Conference.

Figure 4 shows the [C II] to FIR ratio against the

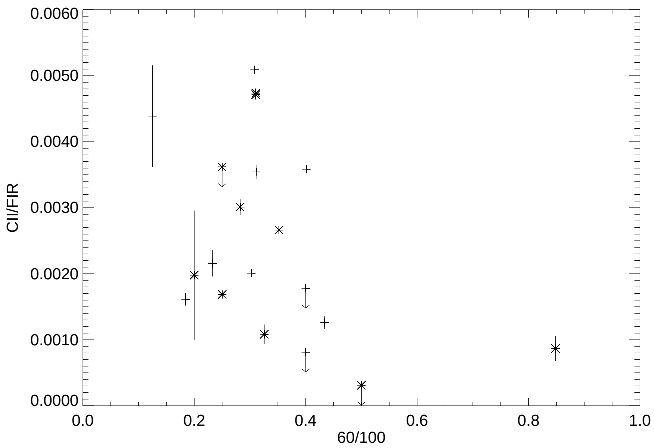

Figure 4. [C II]/FIR ratio against dust temperature, indicated by 60/100 μm ratio. Error bars and upper limits are marked. Core galaxies are marked by '*', periphery by '+'.

dust temperature, as measured by the ratio of the IRAS flux densities at 60 and 100 μm. We note that galaxies with higher f(60)/f(100) have lower values of [C II]/FIR, in agreement with Malhotra *et al.* this conference. There is no apparent relation between the [C II] line/dust colour ratio and position in the cluster or HI mass surface density in the galaxian disks. Therefore, any relation of the [C II] emission to the diffuse HI component of the ISM is not obvious, at least for the central regions of the disks observed. [C II] emission was, however, found to have a strong dependence on basic measurables such as morphology – this will be discussed more in Leech *et al.* in prep.

5. SUMMARY

We have observed 19 normal high surface brightness late-type galaxies from the Virgo cluster with the LWS spectrometer onboard the ISO satellite around the [C II] fine structure line, detecting 15 of these. A good correlation is found between the strength of the [C II] and the FIR flux. Both fluxes increase significantly with later Hubble types. Conversely, no difference can be found in the [C II] properties between the core and periphery galaxies.

REFERENCES

Binggeli B., *et al.* 1985, AJ 90, 1681

Boselli A. *et al.* 1997, AA Supp 121, 507

Cesarsky, C.J. *et al.* 1996, A&A 315, L32

Clegg, P.E. *et al.* 1996, A&A 315, L38

Helou G. *et al.* 1988, ApJS 68, 151.

Kennicutt, R.C., Tamblyn, P., Congdon, C., 1994, ApJ 435, 22

Kessler, M.F. *et al.* 1996, A&A 315, L27

Leech, K.J. *et al.* 1998, 'First ISO Workshop on Analytical Spectroscopy', Eds Heras, Leech, Trams & Perry, ESA SP-419, p279.

Leech, K.J. *et al.* in prep.

Lemke, D. *et al.* 1996, A&A 315, L64.

Lord, S.D. *et al.* 1996 A&A, 315, L117.

Madden, S.C. *et al.* 1993, ApJ 407, 579.

Malhotra, S., *et al.* 1997 ApJ 491, L27.

Malhotra, S., *et al.* 1998, this conference.

Nakagawa, T., *et al.* 1998 ApJS 115, 259.

Pierini, D. *et al.* this conference

Pierini, D. *et al.* MNRAS *submitted*

Sandage, A. Binggeli B., Tammann G.A. 1985, AJ 90, 395.

Smith, B.J., Madden, S.C., 1997 AJ 114, 138

Stacey, G.J. *et al.* 1991, ApJ 373, 423

Tully, R.B., Shaya, E.J. 1984 ApJ, 281, 31

Völk, H. *et al.* *in prep*