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LETTER

Letter to the Editor

Faint [O IV] emission from starburst galaxies*

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Abstract. We report the detection of faint emission in the high-excitation [O IV] 25.90μm line in a number of starburst galaxies, from observations obtained with the Short Wavelength Spectrometer (SWS) on board ISO. Further observations of M 82 spatially resolve the [O IV] emitting region. Detection of this line in starbursts is surprising since it is not produced in measurable quantities in H II regions around hot main-sequence stars, the dominant energy source of starburst galaxies. We discuss various models for the formation of this line. [O IV] that is spatially resolved by ISO cannot originate in a weak AGN and must be due to very hot stars or ionizing shocks related to the starburst activity. For low-excitation starbursts like M 82, shocks are the most plausible source of [O IV] emission.

Key words: galaxies: ISM – galaxies: starburst – infrared: galaxies

1. Introduction

Mid-infrared fine structure lines are powerful probes of dusty and obscured galactic nuclei, being able to penetrate extinctions up to the equivalent of $A_V \sim 50$. Using the Short Wavelength Spectrometer (SWS) on board the Infrared Space Observatory (ISO), it is possible to detect faint lines and sources. The rich observed spectra can be used for a detailed modelling of the ionizing spectra of starbursts (e.g. Rigopoulou et al. 1996, Kunze et al. 1996) and AGNs (Moorwood et al. 1996). Clear differences between their spectra make these lines a valuable new tool for discriminating between AGN and starburst activity in visually obscured galaxies. AGN spectra include emission from highly ionized species and the so-called coronal lines, requiring photons up to ~300 eV for their creation. In contrast, starburst spectra are dominated by lines of low excitation species, because even hot, massive stars emit few ionizing photons beyond the He II edge at 54 eV.

Line ratios like [O IV] 25.9μm / [Ne II] 12.8μm and [Ne V] 14.3μm / [Ne II] 12.8μm have been used by Lutz et al. (1996a) and Genzel et al. (1998) to establish the dominant source of luminosity in ultraluminous infrared galaxies (ULIRGs). In some of the starburst templates studied, very faint [O IV] emission was found, about two orders of magnitude weaker than in typical AGNs. Faint [O IV] emission in starbursts is not relevant for establishing the power source of ULIRGs, but its origin poses an interesting problem because its creation ionization energy is slightly above the He II edge. In this letter we examine possible mechanisms for its production.

2. Observations and data reduction

Observations of a variety of starburst galaxies in the [O IV], [Ne II] and [Ne III] lines have been obtained with the ISO-SWS in 1996 and 1997, as part of a more comprehensive guaranteed time program. In addition, we use data from a raster of SWS observations along the major axis of M 82 obtained on March 16, 1996 in an open time program. One of the target lines of this program was [Fe II] 25.988μm, which is close enough in wavelength to extract the [O IV] line from the same scans.

Integration times of our observations in SWS02 mode were typically 2 seconds per step, i.e. 200 seconds for the complete up-down scan covering the line. We used standard procedures from the SWS Interactive Analysis system for data reduction. For strong sources like bright starbursts, residual fringing is often obvious in the processed data. This was corrected for by fitting sine functions to line-free regions of the spectra. This procedure is sufficiently reliable for the brightest sources, since the fringes can be approximated by a single sine function over the small observed wavelength range near [O IV], and the lines are narrow. Nevertheless, baseline uncertainty due to fringing is often the limiting factor in measuring the [O IV] line flux, and allows us to set only upper limits in some sources. [Ne II] and [Ne III] were always significantly stronger than residual fringes at these wavelengths.

3. Results

Fig. 1 presents the first detection of [O IV] emission in a starburst, in the spectrum of M 82. The line fluxes measured for all our sources are summarized in Table 1, which also compares the [O IV] flux to the flux of lower excitation starburst lines. For this

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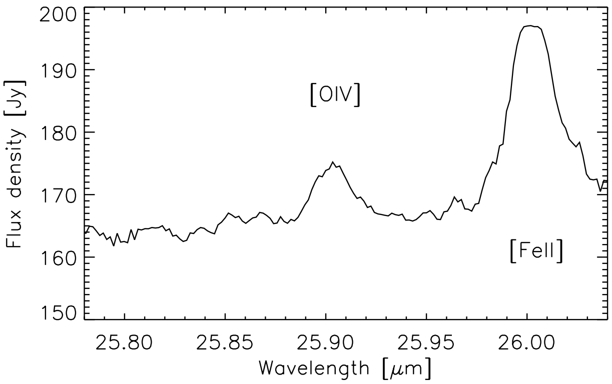

Fig. 1. [O IV] towards the southwest starburst lobe of M 82

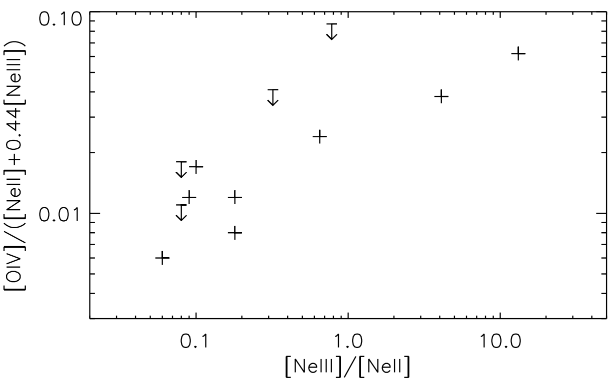

Fig. 2. [O IV] 25.9 μm emission relative to the lower excitation starburst emission for our sample galaxies, plotted against starburst excitation as given by the [Ne III] 15.5 μm / [Ne II] 12.8 μm line ratio

Table 1. Observed line fluxes in starburst galaxies

Source	F([O IV]) 10^{-20} W cm^{-2}	$\frac{[\mathrm{O\,IV}]}{[\mathrm{Ne\,II}]+0.44\times[\mathrm{Ne\,III}]}$
M 82	8.00	0.008
II Zw 40	0.55	0.062
NGC 253	5.00	0.012
IC 342	<1.00	<0.011
NGC 3256	0.93	0.012
NGC 3690 A	<1.20	<0.041
NGC 3690 B/C	0.80	0.024
NGC 4038/39[1]	<0.90	<0.087
NGC 4945	1.40	0.017
M 83	0.80	0.006
NGC 5253	0.65	0.038
NGC 6052	<0.80	<0.127
NGC 6764[2]	<0.80	<0.228
NGC 7552[2]	<1.20	<0.018

[1] Interaction region
[2] [Ne II] and [Ne III] fluxes estimated from observed [S III] (see text)

comparison, we use [Ne II] 12.81μm + 0.44×[Ne III] 15.55μm, the factor 0.44 chosen to give equal weight (by mass) to singly and doubly ionized neon. Contrary to normalizing to just [Ne II] or [Ne III], this measure will be robust to changes in excitation of the starburst proper. For two galaxies without measured neon lines (NGC 6764 and NGC 6052), we have estimated the neon fluxes from the measured [S III] 33.48μm flux using the average scaling for the other sample galaxies.

Accurate linewidths are difficult to determine for the faint [O IV] lines. All the detected lines are consistent in width with the starburst fine structure lines in the same source, that is unresolved or slightly resolved at the SWS resolving power of ∼1000.

Faint [O IV] emission is thus fairly universally detected in starburst galaxies, at the percent level compared to the starburst neon lines. There is a weak correlation of [O IV] strength with excitation of the starburst (Fig. 2). High-excitation, low-metallicity starbursting dwarfs like II Zw 40 and NGC 5253 exhibit relatively stronger [O IV] than low-excitation starbursts, but the effect is not very pronounced compared to the large excitation difference as measured by [Ne III]/[Ne II].

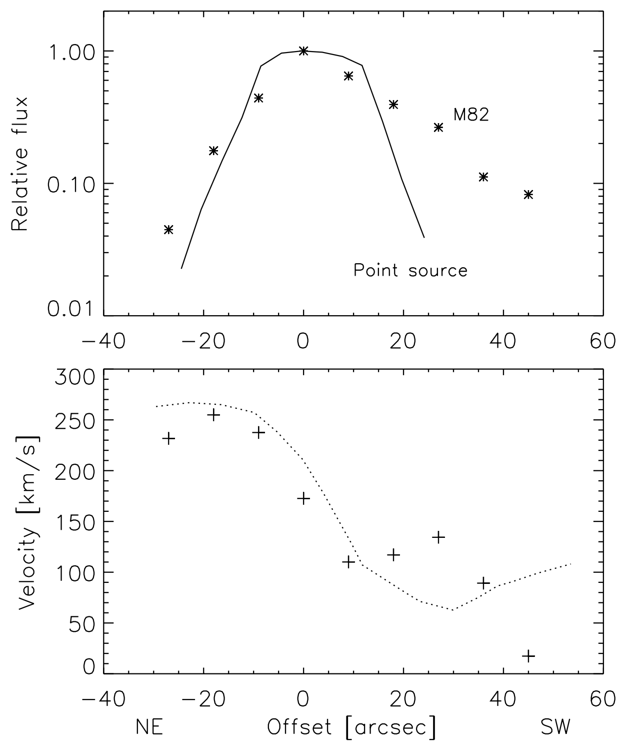

Fig. 3. Top: Spatial profile of [O IV] emission along the major axis of M 82 (symbols) compared to the SWS beam profile for a point source (line). Bottom: Radial velocity curve for [O IV] in M 82 (symbols), compared to the CO radial velocities as presented by Götz et al. (1990). A shift of -50 km/s has been applied to the CO data.

3.1. Spatially resolved [O IV] emission in M 82

The SWS02 raster of M 82 was obtained along the major axis (PA 68°), using a spacing of 9′′. At the time of the observation, the position angle of the long axis of the SWS apertures was 60.9°, i.e. almost aligned to the major axis. We compared the measured [O IV] spatial profile (Fig. 3 top) to the SWS beam profile along the long dimension of the SWS aperture, for the relevant wavelength band (A. Salama, priv. communication). The [O IV] emission is clearly resolved compared to the point source beam profile and must originate in a region similar to the size of the entire starburst region. Further support that [O IV] is resolved comes from the observation that its 'rotation curve' follows the rotation of M 82 (Fig. 3 bottom).

4. Discussion

At a level of just a percent of the strongest low excitation lines, a variety of possible excitation mechanisms for the [O IV] line must be considered.

4.1. Weak AGNs

Because of the great strength of [O IV] emission in Seyfert galaxies, quite faint and perhaps obscured AGNs embedded in a more luminous starburst would contribute sufficient [O IV], with the additional constraint that their narrow line width would have to be small. In fact, hard X-ray observations may indicate AGNs deeply hidden in some of our sources. The case is convincing for NGC 4945 (Iwasawa et al. 1993), but less so for M 82 (Tsuru et al. 1997). For M 82, definite proof against an AGN origin of [O IV] is provided, however, by the fact that the emitting region is spatially resolved and similar in size to the starburst region. If it were illuminated by a central source, sufficient [O IV] could not be produced without exceeding the observed relatively low [Ne III]/[Ne II] ratio.

This constraint is illustrated in Fig. 4, which shows predicted line ratios for a simple AGN photoionization model with varying ionization parameter computed using CLOUDY (Ferland 1996). When [O IV] reaches 1% of the low-excitation neon lines, [Ne III]/[Ne II] is already much too high to be consistent with starbursts like M 82 ([Ne III]/[Ne II]$\sim$0.17, Förster-Schreiber et al., in preparation). This is a fairly general problem in any photoionisation scenario, which persists if one adds a small hard component to a soft starburst spectrum (as discussed below in the context of hot stars). The way to circumvent this problem – postulate small region(s) with very strong [O IV] but small contribution to the total [Ne II] – is not viable here since this would imply a central small NLR which is inconsistent with the observations of M 82. For individual galaxies with [O IV] detections but lacking spatial information, a weak central AGN remains possible. However, we emphasize that the fairly uniform level of the [O IV] detections (Fig. 2) requires an unlikely finetuning of AGN and starburst activity to fit our sample as a whole.

4.2. Super-hot stars

The ionization edge for creation of [O IV] is just beyond the He II edge; at higher energies the spectral energy distributions of most stars drop precipitously. However, a small component of hotter (e.g. Wolf-Rayet) stars might provide the necessary high energy photons. We have run a photoionization model for an H II region excited by a 39000 K main sequence star (represented by a Kurucz model atmosphere), plus an additional 80000 K blackbody to represent a harder component. The blackbody is an ad-hoc choice selected for ease of implementation; however, other strong sources of photons beyond 54 eV would give similar results. As Fig. 5 shows, this attempt fails to explain [O IV] in low-excitation starbursts since the predicted [Ne III]/[Ne II] ratio ($\sim$0.5 to 1) exceeds the observations ($\sim$ 0.1) when [O IV] reaches 1% of the low-excitation lines. For the high-excitation starbursting dwarfs, such a discrepancy does not arise, and hot stars remain an option.

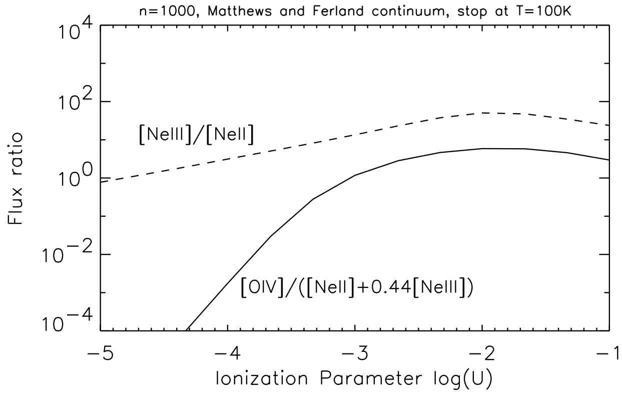

Fig. 4. Photoionization models for [O IV]/([Ne II]+0.44 [Ne III]) (continuous) and [Ne III]/[Ne II] (dashed) as function of ionization parameter in an AGN narrow line region

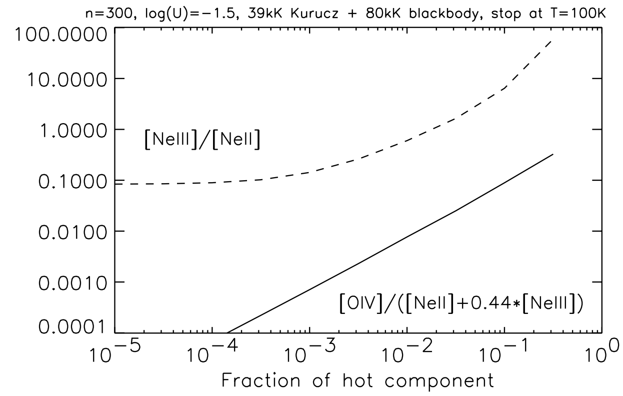

Fig. 5. Photoionization models for [O IV]/([Ne II]+0.44 [Ne III]) (continuous) and [Ne III]/[Ne II] (dashed) in an H II region excited by a 39000 K star, with addition of an 80000 K blackbody contributing different fractions of the total Lyman continuum luminosity

Again, the inconsistency could be alleviated if *small* H II regions with relatively stronger [O IV] emission were dispersed in a lower excitation background. In fact, such a scenario is qualitatively consistent with the observations, as are others with distributed local sources of [O IV]. The major reason to consider it unlikely is that we have failed up to now to detect [O IV] emission even at a *similar* level in local star forming regions, while we would have to postulate regions with *stronger* emission. The Galactic center, which is closest to starburst galaxies in many aspects, still shows [O IV], though even fainter than in the starbursts (Lutz et al. 1996b). In the massive star forming regions W51 IRS2 and 30 Doradus, for which [Ne III]/[Ne II] indicates high excitation, we were unable to detect [O IV] at a level of <0.01 and <0.005 of [Ne II]+0.44[Ne III], respectively (Thornley et al., in preparation).

4.3. Planetary nebulae

High excitation planetary nebulae are a known source of [O IV] emission. A young starburst will, of course, not contain planetary nebulae and it is easy to show that their integrated contribution from the old stellar population is too faint. Evolutionary calculations (e.g. Charlot & Bruzual 1991) show that the contribution of post-AGB stages to the bolometric luminosity is less than 1% even in old populations. Making the extreme assumptions that 10% of the bolometric luminosity is due to an old population and that all PAGB objects are like NGC 7027, one of the highest excitation planetary nebulae, we estimate a robust upper limit of 10^{-20} W cm^{-2} for the [O IV] emission from planetary nebulae in M 82, based on [O IV] flux, luminosity and distance of NGC 7027 as given by Shure et al. (1983) and Beintema et al. (1996).

4.4. Ionizing shocks

There is ample evidence for ionizing shocks in starburst galaxies. Spatially extended, 'Liner'-type optical emission lines can be attributed to shocks, and kinematic mapping sometimes provides direct evidence for outflowing 'superwinds' (Heckman et al. 1990). [O IV] column densities approaching 10^{14} cm^{-2} are expected for modest velocity shocks (100-200 km/s, e.g. Shull & McKee 1979, Dopita & Sutherland 1996). Assuming post-shock values of n=1000 cm^{-3} and T=50000 K, we estimate a 25.90μm intensity of $\sim 3\times10^{-5}$ erg s^{-1} cm^{-2} sr^{-1}, equivalent to $\sim 3 \times 10^{-20}$ W cm^{-2} for the SWS beam. For the assumed conditions, the covering factor of such shocks in the starburst region of M 82 would have to be of the order unity. At higher shock velocities, the [O IV] column would be increasingly dominated by material 'at rest' in the photoionized precursor in the material ahead of the shock front (Dopita & Sutherland 1996). The shock models predict that intensities similar to those estimated for [O IV] are emitted in optical shock tracers like [S II] 6716/31Å. This is fully consistent with optical spectroscopy of M 82 (e.g. Götz et al. 1990). We note that the faint shock emission predicted for the [Ne II] and [Ne III] lines will be completely dominated by the emission from H II regions.

It is instructive to compare the [O IV] results for M 82 with the SWS observations for RCW 103, a bright supernova remnant interacting with a dense molecular cloud (Oliva et al., in preparation). The [O IV] intensities are very similar. The RCW 103 ionic lines are just resolved at the SWS spectral resolving power, again similar to M 82. Ionizing shocks hence are a plausible origin for the M 82 [O IV] emission if their total covering factor approaches unity in the central starburst region of M 82.

5. Conclusion

We have discussed various excitation mechanisms for faint [O IV] emission from starburst galaxies. In general, starburst-related sources and in particular ionizing shocks provide the most plausible explanation. Weak buried AGNs may be plausible for individual sources but can be ruled out for the best studied case of M 82 whose [O IV] emitting region has been spatially resolved. In addition, the fairly small scatter in [O IV] versus starburst luminosity favours a starburst-related origin, since no finetuning of two independent mechanisms is required.

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