Astron. Astrophys. 315, L137–L140 (1996)

ASTRONOMY AND ASTROPHYSICS

What powers luminous infrared galaxies?*

D. Lutz[1], R. Genzel[1], A. Sternberg[2], H. Netzer[2], D. Kunze[1], D. Rigopoulou[1], E. Sturm[1], E. Egami[1], H. Feuchtgruber[1,3], A.F.M. Moorwood[4], and Th. de Graauw[5]

[1] Max-Planck-Institut für extraterrestrische Physik, Postfach 1603, D-85740 Garching, Germany
[2] School of Physics and Astronomy and The Wise Observatory, Tel Aviv University, Tel Aviv 69978, Israel
[3] ISO Science Operations Center, Astrophysics Division of ESA, P.O. Box 50727, E-28080 Villafranca/Madrid, Spain
[4] European Southern Observatory, Karl-Schwarzschildstraße 2, D-85748 Garching, Germany
[5] Space Research Organization of the Netherlands and Kapteyn Institute, P.O. Box 800, 9700 AV Groningen, The Netherlands

Received 17 July 1996 / Accepted 28 August 1996

Abstract. Based on the initial data sets taken with the ISO short wavelength spectrometer (SWS) we present a first discussion of the source of luminosity of (ultra-)luminous infrared galaxies (ULIRGs). By comparison of observations of 2.5-45μm lines to classical starbursts and active galactic nuclei and by modelling of the line emission we show that three key representatives of this class, Arp 220, NGC 6240 and NGC 3256 are likely powered mainly by recently formed, massive stars. While an active nucleus may well be present in anyone of these sources, ratios of fine structure lines in different stages of ionization show that most of the luminosity is in a relatively soft, 'stellar' ultraviolet radiation field. Starburst models with stars of masses up to 50-100 $M_\odot$ successfully account for the observations with an extended burst phase of 1 to 2×10^7 years and burst ages between 2 and 7×10^7 years. Our analysis indicates that previous optical and near-infrared analyses were strongly hampered by the very large extinctions in these galaxies.

Key words: galaxies: Seyfert – galaxies: starburst – galaxies: stellar content – infrared: galaxies

1. Introduction

One of the major discoveries of the IRAS survey was the identification of a class of very luminous ($L\geq10^{11.5}$ $L_\odot$) galaxies emitting most of their energy at far-infrared wavelengths (for a review see Sanders & Mirabel 1996). However, the nature of the primary energy source(s) in these infrared luminous galaxies has, so far, remained elusive. Based on their far-infrared, millimeter, and radio properties many authors have argued that active star formation dominates. Their optical properties, on the other hand, often resemble narrow line active galactic nuclei (AGNs), with a few broad line examples. Some of them contain compact radio nuclei, again indicative of hidden AGNs. However, being reprocessed radiation, the far-infrared and radio continuum are not very specific with respect to the nature of the primary energy source. Optical, near-infrared and soft X-ray photons from the nuclear regions of these obscured objects suffer strongly from dust extinction and are at best qualitative tools for studying the central energy source(s). With the advent of the Infrared Space Observatory (Kessler et al., this volume), sensitive mid- and far-infrared spectroscopy, which is much less susceptible to extinction, has become available as a new, specific tool for investigating the nuclei of obscured galaxies.

2. Observations

The SWS observations discussed here were taken in the SWS01 and SWS02 modes during the first months of the ISO mission. We refer to de Graauw et al. (this volume) for a description of SWS. The SWS data of several sources are discussed in greater depth in other contributions in this volume: the Galactic center by Lutz et al., NGC 3256 by Rigopoulou et al., NGC 4038/39 by Kunze et al., Arp 220 by Sturm et al., and Circinus by Moorwood et al.. Observations of NGC 6240, NGC 4945, Cen A, NGC 7582, NGC 5253 and M 82 will be discussed in more detail in forthcoming papers. Here we will concentrate on *a comparison and first theoretical analysis*, with emphasis on the *nature of the dominant luminosity source(s)*.

3. Results

The basic observational results are listed in Table 1 and Figures 1 and 2. Table 1 lists global quantities, [Ne II] 12.8μm fluxes observed with SWS, extinction corrected [Ne II] luminosities, [Ne III]15.6μm / [Ne II]12.8μm ratios and effective temperatures for the UV radiation field derived from this ratio (Sect.

Send offprint requests to: D. Lutz

* Based on observations with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) and with the participation of ISAS and NASA. The SWS is a joint project of SRON and MPE

Table 1. Properties of starburst-dominated galaxies

Source	D	L_{Bol}(FIR)	A_V^{scr}	A_V^{mix}	L_{Lyc}(IR rec)[6]	$\frac{Bol}{Lyc}$	F(NeII)	$L(NeII)_0$	$\frac{Bol}{60*NeII}$	$(\frac{NeIII}{NeII})_0$	T_{eff}(UV)
	[Mpc]	[$L_\odot$]	4	5	[$L_\odot$]		[W/cm^2]	[$L_\odot$]			[K]
G.C.[1]	8.00(-3)	3.0(7)	30		3.0(6)	10	4.5(-16)	2.7(4)	18	7.5(-2)	37000
M82[2]	3.25(0)	2.0(10)		20	2.5(9)	8	1.1(-17)	5.2(7)	7	2.1(-1)	42000
N4945	4.00(0)	2.0(10)		100	6.0(8)	33	7.4(-19)	1.4(7)	24	9.0(-2)	41000
N4038/39	2.10(1)	2.5(10)		70	4.5(9)	6	8.0(-20)	2.8(7)	15	8.0(-1)	44000
N5253	4.00(0)	8.0(8)	3		1.7(8)	5	4.6(-20)	2.6(5)	52	5.5(0)	48500
N3256	3.70(1)	3.0(11)		35	2.9(10)	10	8.0(-19)	6.1(8)	8	1.5(-1)	42000
N6240[3]	9.50(1)	5.0(11)		40	1.2(10)	42	1.7(-19)	9.2(8)	9	3.4(-1)	42500
Arp 220	7.70(1)	1.3(12)	50		1.7(11)	8	5.2(-20)	6.1(8)	36		

[1] The Galactic center fluxes/luminosities have been multiplied by 5 to account for the 'escaping' flux
[2] M82 values are for the central 30"
[3] N6240 extinction from Pα, Brγ, and near-IR continuum colors
[4] Visual extinction from a combination of recombination lines (Brγ,Brβ, Brα, Pfα) and [S III] 18 and 33μm
[5] Same as [4] but in the approximation where dust and gas are fully mixed. We list either [4] or [5] depending on the better fit
[6] Lyman continuum luminosity inferred from infrared H recombination lines

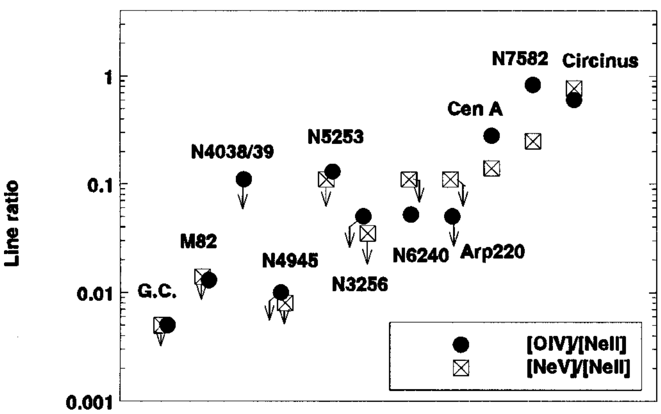

Fig. 1. Dereddened ratios (or 3σ upper limits) of high excitation lines with respect to [Ne II]. From left to right, we plot the five starburst template galaxies, three (ultra)luminous IRAS galaxies, and three active galactic nuclei.

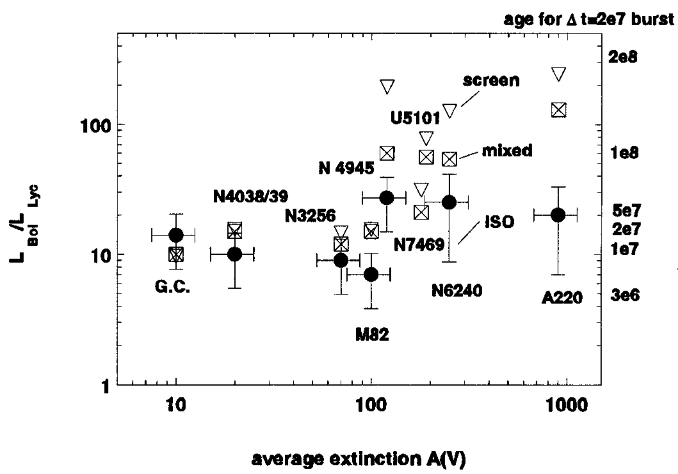

Fig. 2. Ratio of bolometric luminosity to hydrogen ionizing luminosity, plotted as a function of dust content of the source expressed as an *average* dust extinction. The average extinction was obtained from the CO 1-0 2.6mm line, using standard Galactic conversion factors from CO flux to H_2 column density and from hydrogen column density to visual extinction. Triangles denote the data points where L_{Lyc} is determined from the 2.1μm Brγ line with a correction for a foreground dust screen taken from optical/near-infrared line ratios (e.g. Hα/Brγ) or continuum colors (e.g. V-K, or J-K). Rectangles denote data points where L_{Lyc} is determined from the same data, but with extinction corrections for the case where absorbing dust and emitting gas are fully mixed. Filled circles with error bars denote data points where L_{Lyc} is determined from the new ISO SWS hydrogen recombination line and [Ne II] data.

3.1). We list visual extinctions for either the screen or full mix cases depending on what best fits the data for a particular source. Fig. 1 is a plot of the dereddened [O IV]25.9μm / [Ne II]12.8μm and [Ne V]14.3μm / [Ne II]12.8μm ratios. Fig. 2 gives the ratio of total to ionizing luminosities (L_{Bol}/L_{Lyc}) derived from different extinction corrections.

3.1. Effective temperature of the radiation field

The infrared fine structure lines discussed here arise in H II regions that are photoionized by stars or a central active nucleus. Estimates of the effective temperature can be obtained from line ratios of different ionic states in the same atom ([NeIII]15.6μm/[NeII]12.8μm, [S IV]10.5μm/ [S III]18.7μm, [Ar III]8.9μm/[Ar II]6.9μm). Electron densities can be obtained from the [Ne III] 36.0/15.6μm and [S III] 18.7/33.5μm pairs and yield $n_e \sim 10^2$ to $10^{2.5}$ cm^{-3} in M 82 and NGC 3256. Assuming that typical source sizes are comparable to the overall size of the starburst, electron densities of $\sim$ 300cm^{-3} and the measured Lyman continuum luminosities yield a typical ionization parameter log (U)$\sim$-2.5. Using the photoionization codes CLOUDY (Ferland 1993) and ION (Netzer 1993) and stellar input spectra from Kurucz (1992) for solar metallicity we then determined the best fitting stellar effective temperatures from the [Ne III]/[Ne II] line ratio. Table 1 lists the effective temperatures for the starbursts and the two luminous IRAS galaxies NGC 3256 and NGC 6240.

The line ratio in most sources including the two ULIRGs is reasonably well fit by effective temperatures near 42,000 K. The Galactic center (here we used $n_e \sim 3000$ and log(U)=-1) lies at the cool end of the distribution, a fact that is very likely explained by the ageing effects of its most recent star formation epoch. The H II region galaxy NGC 5253 lies at the other extreme of the distribution, most likely a result of its low metallicity. In the Galactic center, M 82 and NGC 3256 effective temperatures derived from [S IV]/[S III] and [Ar III]/[Ar II] agree satisfactorily with the values from [Ne III]/[Ne II]. Using the most recent models of Sellmaier et al. (1996 and priv. comm) reduces the effective temperatures by 1000 to 2000 K as compared to the Kurucz models.

3.2. High excitation lines: signature of a hidden AGN?

We have also observed several high excitation lines that require a much harder radiation field than can be produced by stars and thus are signposts for an AGN. Fig. 1 is a plot of the dereddened [Ne V]/[Ne II] and [O IV]/[Ne II] line ratios (or 3σ upper limits) for the three luminous IRAS galaxies in our sample along with the starburst and AGN templates. Again these ratios are fairly insensitive to extinction. In all sources known to be powered by stars alone the [Ne V]/[Ne II] and [O IV]/[Ne II] ratios are $\leq$0.1, while these ratios are between 0.13 and 1 in the three AGNs. All three luminous IRAS galaxies also have line ratios $\leq$0.1, strongly supporting the notion that an (even moderately extincted) AGN cannot be the main source of their luminosity. The only way out of this important constraint is to postulate that these sources contain AGNs that are hidden even at 15 to 30μm, corresponding to $A_V \geq 50 \ldots 200$ ($N(H_2) \geq 1$ to 4×10^{23}). However, as we will show, the strengths of low excitation lines are consistent with starbursts powering the entire luminosity. We thus conclude that *Arp 220, NGC 6240 and NGC 3256 are powered mainly by stars.* However, it is of course possible that an AGN contributes a fraction of the bolometric luminosity.

3.3. Massive star formation in luminous IRAS galaxies has been recent

For Arp 220, NGC 6240, and NGC 3256, a number of near-infrared/optical studies in the literature discuss starburst scenarios. (e.g. Lester et al. 1988, Thronson et al. 1990, Doyon et al. 1992, van der Werf et al. 1994, Moorwood and Oliva 1994, Armus et al. 1995, 1996, Larkin et al. 1996). Investigations of Arp 220 and NGC 6240 concluded that the observed far-infrared luminosity is not dominated by recently formed, massive stars, implying that the last period of very active star formation must have occurred $\gg10^8$ years ago or that stars more massive than 20 to 30 $M_\odot$ have recently not been forming. The reason for this conclusion are the small equivalent widths and fluxes of ionization tracers such as Hα or Brγ, leading to a ratio of bolometric (IRAS) to ionizing luminosity (L_{Bol}/L_{Lyc}) larger than in young starbursts.

There are, however, indications that the extinction measures used in these analyses are insufficient. We have used CO 2.6mm fluxes to derive an *average* extinction using Galactic conversion factors from CO flux to H_2 column density and visual extinction. Since the average extinction is somewhat uncertain due to the adopted conversion factors, and not identical to the extinction along a particular line of sight, it is not used for extinction correction of observed quantities. It provides, however, an identification of galaxies which, due to their large gas and dust content, might suffer from very high extinction to their active regions. If the very large average extinction found in ULIRGs is characteristic of the star forming zones then optical and near-infrared observations cannot possibly probe the sources of luminosity.

To demonstrate this we plot in Fig. 2 L_{Bol}/L_{Lyc} as a function of the CO-derived average extinction. We have added the luminous galaxies NGC 7469 and UGC 5101 which we have observed in the near-infrared with high resolution imaging spectroscopy (Genzel et al. 1995, 1996). The open triangles show the location of the different sources if a screen extinction model is adopted with extinction values derived from optical and near-infrared tracers. While all star formation templates (and the luminous galaxy NGC 3256) have L_{Bol}/L_{Lyc} ratios fully compatible with current or recent, massive star formation ($L_{Bol}/L_{Lyc} \sim$10), NGC 7469, NGC 6240, UGC 5101 and Arp 220 range between $L_{Bol}/L_{Lyc} \sim$ 30 and 300 which cannot be explained by recent star formation, or only by extreme scenarios (large age, low upper mass cutoff). There is a trend of larger L_{Bol}/L_{Lyc} ratios for sources with larger average extinction, indeed indicating that the extinction estimates may be insufficient.

An improvement in the analysis is the recognition that often a model where the absorbing dust is fully mixed with the emission regions is a better description of the near-infrared/optical data. After application of these extinction corrections (filled rectangles in Fig. 2) all L_{Bol}/L_{Lyc} ratios in the luminous IRAS galaxies are reduced significantly, but for UGC 5101, NGC 6240, and Arp 220 still not sufficiently to fit normal starburst models.

The new ISO data now suggest that observations at mid- and far-infrared wavelengths are required to penetrate the dust enshrouding the sources of luminosity in the luminous IRAS galaxies. For the extinction values listed in Table 1, even the observed mid-infrared [Ne II], [S III] etc. lines are subject to significant attenuation and require upward corrections by factors between 1 and 4. The filled circles with error bars in Fig. 2 denote the L_{Bol}/L_{Lyc} ratio determined from the new SWS observations. As an estimate for L_{Lyc} we used the extinction corrected Brα, Brβ or Pfα fluxes, or scaled the extinction corrected [NeII] luminosity by 60 (or an average of these, e.g. Arp 220 and NGC 3256). The latter factor is characteristic for the starburst templates with known L_{Lyc}. ¿From the new ISO SWS data we thus conclude that *the L_{Bol}/L_{Lyc} ratio in Arp 220, NGC 6240 and NGC 3256 is similar to its value in starburst galaxies, and that massive stars have, in fact, been forming there within the last few tens of million years*. For UGC 5101 detailed 3D near-infrared imaging spectroscopy suggests the same conclusion (Genzel et al. 1996). The reason why these galaxies look like

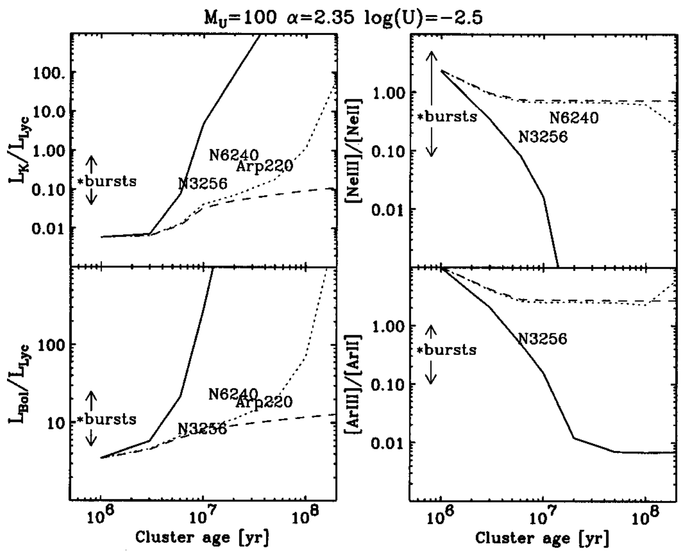

Fig. 3. Ratios of bolometric, ionizing and K-band luminosities, and characteristic infrared line ratios for evolving star cluster models. Solid curves denote δ-bursts, dotted curves denote decaying bursts with 2×10^7 yr timescale, dashed curves are constant star formation models.

old, 'burnt out' bursts at short wavelength is the very large extinction of the star forming regions.

3.4. Starburst models

We have used the star cluster evolution code of Kovo and Sternberg (1996) to calculate the global L_{Bol}/L_{Lyc} and L_K/L_{Lyc} as a function of time in three different star formation histories: pure δ-bursts, extended bursts (decaying with Δt=2×10^7 years) and constant star formation. We carried out calculations for Salpeter IMFs, solar abundances and upper mass cutoffs of 25, 50 and 100 $M_\odot$. We synthesized the cluster-averaged stellar spectrum by coadding Kurucz atmospheres with the appropriate weighting of different stellar types as derived from the Kovo and Sternberg code. We then calculated the various characteristic infrared line ratios with the ION photoionization code with log(U)=-2.5 and n_e=300 cm^{-3}. The results for the specific case of m_u=100 are plotted in Fig. 3 which also shows the location of the ULIRGs and the parameter range for starburst templates that we have observed. Constant star formation models and models with low upper mass cutoffs ($M_u \sim 25 M_\odot$) do not fit any of the objects. δ bursts fit localized regions very well (e.g. the overlap region of NGC 4038/39). The best overall fits for both starburst templates and the ULIRGs observed so far are for moderately extended bursts (Δt=1-2×10^7 years) with mean ages ranging between 1 to 7×10^7 years and high upper mass cutoffs (50 to 100 $M_\odot$). ULIRGs tend to require somewhat older ages than the starburst templates but otherwise are very similar.

There remain still substantial uncertainties in our conclusions. First it will obviously be necessary to observe a larger sample of ultraluminous galaxies before we can be sure that our conclusions are generally applicable and before it is clear whether our findings fit into an evolutionary scheme; this is the purpose of additional observations with ISO. Second while the general conclusion that the ULIRGs discussed here are powered by massive stars is robust, the detailed constraints on the starburst properties are still somewhat uncertain. As mentioned above, the stellar atmosphere models by Sellmaier et al. (1996) predict more energy output in the 20 to 50eV range than the Kurucz models and thus require less massive stars for the same [Ne III]/[Ne II] etc. ratios. Line fluxes, line ratios and extinction corrections are all subject to $\sim \pm30\%$ calibration uncertainties and to uncertainties in the extinction law (Lutz et al., this volume). Finally, future detailed studies with ISO will need to address the issues of metallicity, the effect of dust within the H II regions on the line emissivity, and the range of ionization parameter and gas density.

Acknowledgements. We thank the SRON-MPE SWS team and the SIDT for their dedicated work. SWS and the ISOSDC at MPE are supported by DARA grants 50 QI 8610 8 and 50 QI 9402 3. SWS acknowledges contributions from KULeuven, Steward Obs. and Phillips Lab. This work has been partly supported by the German-Israel Foundation grant I-196-137.7/91.

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