GAS PROBED BY MIR AND FIR SPECTROSCOPY

J.M. van der Hulst
Kapteyn Astronomical Institute
Groningen, The Netherlands.

Abstract

In this paper I briefly discuss the various spectral lines in the mid- and far Infrared that can be used to probe the physical conditions of the interstellar medium (ISM) in a variety of circumstances. I will discuss the cold molecular phase of the ISM probed by the rotational lines of H_2, the cool diffuse ISM probed by the major cooling line of [CII] and the hot gas in HII regions which can be probed by fine structure lines of a number of elements and H-recombination lines.

1 Introduction

The advent of modern spectroscopic capabilities in the Infrared (IR), both from the ground and from space, has offered unique opportunities for probing the interstellar medium (ISM) over a range of physical conditions. Additional advantage of working in the IR is that one is not affected as much by extinction as in the optical part of the spectrum, so that one can probe obscured regions of the ISM such as dark clouds, galactic nuclei etc..

The ISM is a very important component of galaxies and plays a crucial role in its evolution. There is a subtle interplay interplay between the stars formed from the dense phases of the ISM and the ISM itself: *e.g.* the stellar life cycles are intrumental for the enrichment of the ISM, stellar winds and supernova explosions determine the structure and energetics of the ISM, and hence influence the continuing star formation process. The radiation field from the stellar component of galaxies determines the ionization and heating of the various components of the ISM both locally (*e.g.* HII regions around young star clusters) and globally (heating and ionization of the diffuse medium by the general interstellar radiation field). In the 70's the concept of a multiphase ISM was developed [12] (see also [21] and [44]). Cold, dense and warm, tenuous gas coexist in pressure equilibrium. Later a hot phase was added to this picture to account for the observed X-ray emission [26]. In this paper I will only discuss the cold, cool and warm phases.

Table 1. Relevant components of the ISM

Objects	Temperature	Density	IR Lines
Cold Gas	10–100 K	1–1000 cm^{-3}	H_2, PAH's
HII regions	$10^3 - 10^4$ K	3–300 cm^{-3}	[OII], [OIII], etc.
Diffuse HI	$10^2 - 10^3$ K	0.1 cm^{-3}	[CII], [OI]

Table 1 provides an overview of the nomenclature and associated ranges in temperature and density of the regimes I will discuss. These are: (i) the cold, molecular component, which in the IR is traced by the presence of PAH features and the rotational lines of H_2; (ii) the diffuse neutral medium, which can be traced by the [CII] and [OI] lines; (iii) the ionized medium (*i.e.* predominantly the HII regions), which can be traced by the IR H-recombination lines and a large number of fine structure lines of elemensts such as O, N, S, Ar, Ne, and Si.

2 The Cold Molecular Gas

Cold molecular gas is usually studied by observing mm- and sub-mm spectrallines, which result from rotational and vibrational transitions of diatomic and polyatomic molecules [14]. A large number of molecules has been detected which can be used to trace different regimes of density and temperature and to study the interstellar chemistry [6]. The most abundant molecule (H_2), however, cannot easily be observed directly and its column density is usually inferred from the intensity of the CO emission lines, assuming a H_2/CO conversion factor [14], [19].

2.1 Observing H_2

H_2 has been detected directly by UV absorption in translucent clouds [49], [11]. Measuring H_2 directly through its rotational lines in the far IR (0–0 S(0) at 28.2 μm, 0–0 S(1) at 17.0 μm and 0–0 S(2) at 12.3 μm) is very difficult. The gas has to be very cool (10–400 K) and must be present in large columns as the transition probabilities are very low. Warm H_2 has been observed near star forming regions through its near IR ro-vibrational transitions around 2 μm in the Galaxy [42], [50], the Magellanic Clouds [18] and the nuclei of other galaxies [20]. This gas is usually excited by shocks or fluorescent mechanisms [3] and reaches temperatures of 1000–5000 K.

2.2 New Observations

With ISO it is possible for the first time to attempt to measure the rotational lines of H_2 directly using the Short Wave Spectrometer (SWS). Observations of the nuclear region in the face-on galaxy NGC 6946, which is quite rich in molecular gas, led to a detection of the 28.2 μm S(0) and the 17.0 μm S(1) line [47]. This observation implies the presence of about 5 10^6 $M_\odot$ of H_2 with a temperature of about 170 K, so quite warm, possibly because of the nuclear environment. H_2 rotational lines of warm gas have also been detected in the starburst nuclei of Arp 220 [43], Circinus [28] and NGC 3256 [39], and in the interacting galaxy pair NGC 4038/39 [22].

Attempts are being undertaken to observe the rotational transitions in the disks of edge-on galaxies, where the expected column densities are high. Those results will be forthcoming.

3 The Cool Neutral Component

The diffuse ISM, most commonly traced by the 21-cm HI line, depends for its cooling on both the 21-cm transition itself and on the 158 μm [CII] line (and to a lesser extend on the 63 μm [OI] line) [5]. The [CII] line also is a major coolant for PDRs (photon dominated or photodissociation regions) [14], [45], [46], and can hence also be used to study the much denser (see table 1) molecular cloud surfaces. These are discussed in detail elsewhere in these proceedings. Here I will concentrate on the diffuse ISM.

3.1 Cooling of the diffuse ISM

Carbon is the most abundant element with an ionization potential (11.3 eV) below the 13.6 eV of Hydrogen and hence CII ions are present in large quantities in neutral atomic clouds in the ISM. The ground state of the CII ion is split into two levels (the $^2P_{3/2}$ and $^2P_{1/2}$ level) with an energy difference (in temperature units) of 91 K or a wavelengths of 157.7 μm. The critical density, *i.e.* the density at which collisional excitation balances radiative de-excitation, is about 4 10^{-3} cm^{-3}. The CII ions are excited by collisions with electrons and Hydrogen atoms and cool radiatively. Therefore the [CII] 158 μm line is the major coolant for the diffuse, neutral ISM [5]. If one calculates the cooling rate per nucleon as a function of temperature for different pressures (figure 1, [21]) it becomes clear that the [CII] line is a good probe of pressure. Figure 1 shows clearly that for a given average pressure of the ISM the cooling rate has little dependence on temperature for $50 < T < 400$ K. This means that it is possible to estimate the average pressure of the ISM with a measurement of the [CII] line strength and the particle density n (from HI and CO observations).

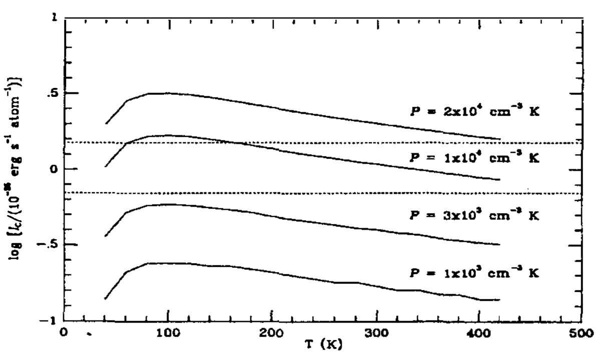

Figure 1: Plot of the [CII] cooling rate per nucleon in cool clouds as a function of temperature for 4 different values of the gas pressure ($P = nT$). Carbon is assumed to be depleted by 50% and a cosmic ray ionization rate of 10^{-16} s^{-1} is assumed [21].

In a multi-phase ISM in pressure equilibrium, where the pressure is to first order determined by the supernova rate [26], it is clearly of interest to actually try to measure pressure directly. The pressure has important influence on the relative masses, column densities, volume filling factors etc. of the different phases. The pressure for example determines the relative proportion of atomic and molecular medium in the ISM (since it affects the location of the shielding layer where the HI /H_2 transition occurs) [10]. It is furthermore of interest to verify whether galaxies have radial pressure gradients, which one might expect because the midplane pressure is also determined by the weight of the overlying halo gas.

3.2 Observations

Measurements of the ISM pressure have recently been attempted in NGC 6946 using the KAO [25]. If most ($\sim 50\%$) of the extended, diffuse [CII] emission is interpreted as originating from the diffuse, cool ISM, a pressure of $6.3\ 10^3 - 1.0\ 10^4$ cm^{-3} K is inferred. This is not very different from the pressure found for HI clouds in the Galaxy based on UV absorption measurements of the CII ions [21], [36]. New determinations of the cooling rate of the diffuse medium in the Galaxy from observations of the 158 μm [CII] line with FIRAS on board of COBE [4] confirm that a very large fraction of the extended [CII] flux arises from the cool medium. The derived cooling rate is, however, lower ($2.7\ 10^{-26}$ ergs s^{-1} (H atom)$^{-1}$) and the corresponding pressure is only 2000 cm^{-3} K. Independent observations of the 158 μm [CII] line with the Japanese experiment IRTS [40], [29] give an even lower cooling rate of $6\ 10^{-27}$ ergs s^{-1} (H atom)$^{-1}$, so there apparently is large uncertainty regarding the precise values. In part this depends on parameters such as clumpiness and filling factors and a good estimate of what fraction of the [CII] emission originates from the diffuse medium. In the extended disk only a small fraction is expected to be due to PDR's or ionized gas such as HII regions and the warm ionized medium (WIM).

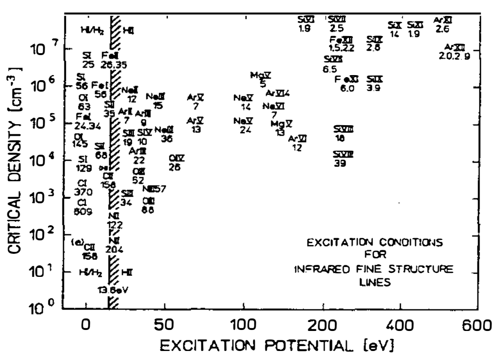

Figure 2: Overview of the infrared fine structure lines as a function of excitation potential and critical density [14].

Observations of the 205 μm [NII] line can in principle give a handle on the contribution from the WIM. The COBE FIRAS data show that at least in our Galaxy the emission in this line is dominated by the WIM [4], so that the strength of the [NII] line can be used to estimate the [CII] emission from the WIM. This of course requires knowledge of the C^+/N^+ ratio. Fortunately most of the C and N will be in the form of C^+ and N^+ under normal ISM conditions [37].

This method for determining the pressure of the ISM appears quite promising and will be applicable to several nearby galaxies which the Long Wave Spectrometer (LWS) on board of ISO will map in the [CII] line. The [NII] 205 μm unfortunately is outside the LWS window, but instead the [NII] 122 μm line can be used to estimate the contributions from the WIM.

4 The Ionized Component

The IR wavelength range covered by ISO offers a large number of lines for probing the physical conditions of the ionized components of the ISM. In particular objects with reasonably high surface brightness such as planetary nebulae, HII regions and the star forming regions around active nuclei. Here I will concentrate on HII regions and discuss some of the related problems. These are also relevant for other objects such as PNe and galactic nuclei, insofar the line emission is due to photoionization by a stellar continuum. The IR fine structure lines are mainly sensitive to electron density (n_e). Figure 2 [14] shows a number of IR fine structure lines as a function of excitation energy and critical density and can be used directly to get an idea which lines probe which regime of density and excitation. The atomic and molecular clouds discussed in sections 2 and 3 can be probed using transitions with excitation potentials < 13.6 eV. The lines in the regime $13.6 - 60$ eV probe the conditions in HII regions where lines > 60 eV trace the high excitation conditions present in *e.g.* galactic nuclei where shocks and/or photo ionization by a power law continuum play an important role. Table 2 provides a list of prominent IR fine structure lines.

Table 2. Infrared Line Transitions

Species	Excitation Potential (eV)	λ μm	n_{crit} cm^{-3}	Species	Excitation Potential (eV)	λ μm	n_{crit} cm^{-3}
OI		63.18	$5\ 10^5$	SIII	23.33	33.48	$2\ 10^3$
OI		145.5	$9\ 10^4$	ArIII	27.63	8.99	$3\ 10^5$
FeII	7.87	25.99	$2\ 10^6$	NIII	29.60	57.32	$3\ 10^3$
SiII	8.15	34.81	$3\ 10^5$	SIV	34.83	10.51	$6\ 10^4$
CII	11.26	157.7	$3\ 10^3$	OIII	35.12	51.82	$5\ 10^2$
NII	14.53	121.9	$3\ 10^2$	OIII	35.12	88.36	$4\ 10^3$
NII	14.53	203.5	$5\ 10^1$	NeIII	40.96	15.55	$3\ 10^5$
ArII	15.76	6.99	$2\ 10^5$	NeIII	40.96	36.02	$4\ 10^4$
NeII	21.56	12.81	$5\ 10^5$	OIV	54.93	25.87	$1\ 10^4$
SIII	23.33	18.71	$2\ 10^4$				

4.1 The Physics

For the basic priciples of line formation in an astrophysical plasma the reader is referred to [2] and [30]. For the analysis and interpretation of line strenghts and line ratios of spectra one usually tries to find line ratios which are sensitive to either electron temperature (T_e) or density (n_e). Once those have been estimated one can calculate the ionization structure of elements and estimate elemental abundances.

Electron density n_e can be measured by observing the effects of collisional de-excitation of lines originating from levels with approximately the same excitation energy. The level populations will then depend on density and hence the line strenghts (assuming that atomic properties such as radiative transition probabilities and collisional (de-)excitation rates are known) will also measure density. Examples are the [OII] $\lambda3729/\lambda3726$ and [SII] $\lambda6716/\lambda6731$ doublets [30]. For measuring temperature one requires ions with upper levels with considerably different excitation energies, where the excitation rates usually depend strongly on T_e. The classical example here are the [OIII] $\lambda4363$ line from the upper ^{1}S level and the [OIII] $\lambda4959/5007$ doublet

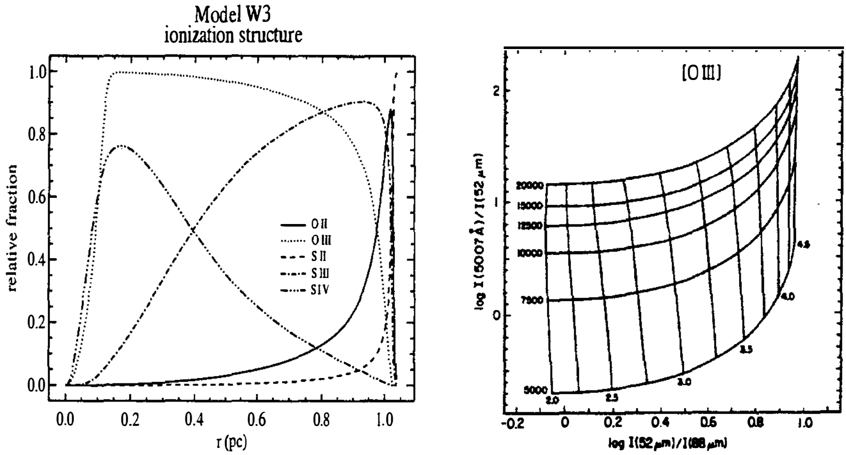

Figure 3: Left panel:Ionization structure for S and O in a model for the Galactic HII region W3 (courtesy P.A.M. van Hoof). Right panel: The [OIII] temperature-density plane defined by ratios of the 5007 Å, 52 μm and 88 μm lines. The lines give line ratios for a number of values for log n_e and T_e [7].

from the lower ^{1}D level. If the [OIII] λ4363 line is undetectable one cannot measure T_e. In that case abundances are measured using an empirical method involving the [OIII] λ4959/5007 and [OII] λ3729/3726 doublets [9].

The main problem inherent to these methods is that one uses different ions for measuring T_e and n_e and that it is not at all clear that these probe the same nebular material. In fact, depending on *e.g.* metallicity, they often do not [13], [31], [32], [33], [34]. Figure 3a shows the ionization structure of a model for the Galactic HII region W3 as an example. It is quite obvious that the region where the [SII] lines used for measuring n_e arise has little overlap with the region where the [OIII] lines are produced. Consequently one will derive erroneous elemental abundances [13]. This problem is usually countered by introducing a fluctuation parameter t^2 which measures the deviations from an average T_e in an inhomogeneous nebula [7], [8], [13], [31].

Use of the density dependent IR fine structure lines offers a possibility to circumvent this problem entirely [7], [8], [9]. If one finds ions which both have IR doublets and optical line transitions one can use the IR doublet line ratio to get density and the optical/IR line ratio to get temperature. The main advantage lies in the use of a single ion and hence the assurance that one measures the properties of the same nebular material. A good example are the [OIII] 5007 Å, 52 μm and 88 μm lines [7]. Figure 3b illustrates how use of the 5007 Å/52 μm line ratio and the 52 μm/88 μm line ratios can disentangle n_e and T_e. This methed has been applied to KAO observations of PNe [7].

4.2 Observations

Quite some work has been done on Galactic HII regions using the KAO [1], [15], [16], [23], [24], [27], [35], [41]. These studies used a range of IR lines: [NeII] 12.8 μm, [ArII] 7.0 μm, [ArIII] 9.0 μm, [SIII] 18.7 μm, [SIV] 10.5 μm, [OIII] 52 and 88 μm, and [NII] 57 μm. This work traces the abundances of these elements as a function of galactocentric radius. A great advantage

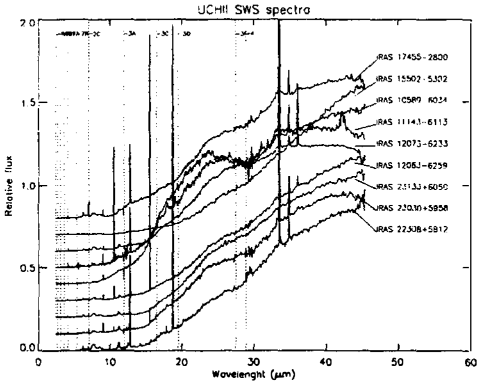

Figure 4: ISO SWS spectra of a few compact HII regions in the Galaxy [38]. Note the prominent emission lines of [NeII] at 12.8 μm, [NeIII] at 15.6 μm, [SIII] at 18.7 and 33.5 μm. In some HII regions one can also distinguish the 36 μm [NeIII] line and the 35 μm [SiII] line.

is that HII regions which are optically obscured are accessible in the IR. A major difficulty is to properly correct for the aperture differences of the observations of the different lines, when combining data to get diagnostic line ratios. An interesting result is a general increase in N/O with decreasing galactocentric radius, indicating secondary production of N with respect to primary processed O in the inner parts of the Galaxy [1], [24].

At present this kind of study is being done with ISO [38], with the great advantage that more spectral lines are available as can be seen from figure 5 which shows SWS spectra of 9 compact HII regions in the Galaxy. Note the differences in strength of the various fine structure lines. In additon the continua of these HII regions are quite different indicating different dust contents and temperatures. Another indication of the wide range in properties is the variation from object to object of the broad PAH features [38].

With ISO it is also possible to get spectra from bright HII regions in nearby galaxies. Various observing programs focus on this but definite results are not yet available. One such programs focusses on HII regions in the Magellanic Clouds. These have the advantage that they have fairly high surface brightness (and are hence easily detectable) while complementary optical spectroscopy from the ground is not hampered by the same severe extinction problems which exist for Galactic HII regions. This implies that an analysis such as outlined for [OIII] in the previous section can be much more easily carried out.

Preliminary spectra from LWS and SWS observations of the bright HII region N160A ([17], [48]) in the LMC are shown in figures 5 and 6. Analyses of the spectra and combination with optical spectroscopy, followed by modelling using photo ionization models will be forthcoming. A preliminary analysis and modelling of the compact HII regions N81 and N88 in the SMC shows that there is reasonably good agreement between nebular models and the IR and optical spectroscopy.

Acknowledgements. I am very grateful to Trinh Thuan and Gary Mamon for the opportunity to participate in the XVIIth Moriond Astrophysics Meeting.

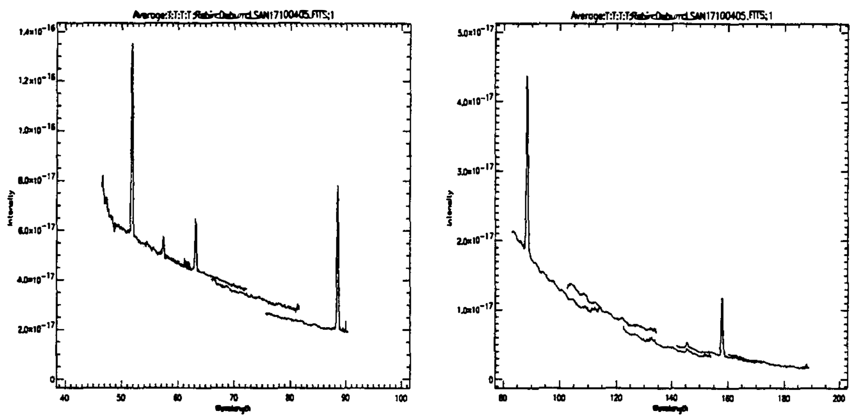

Figure 5: ISO LWS spectra of the HII region N160A in the LMC (Courtesy J.-P. Baluteau). Note the prominent lines of [OIII] at 52 and 88 μm, [CII] at 158 μm, [OI] at 63 μm and [NIII] at 57 μm.

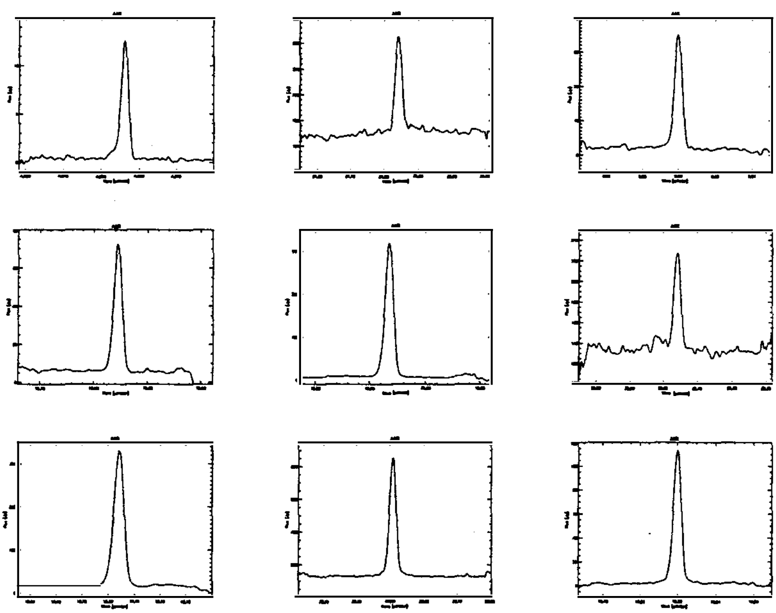

Figure 6: ISO SWS spectra of the Brα line and a number of fine-structure lines in the HII region N160A in the LMC. From top left to bottom right: Brα 4.05 μm, [SiII] 35 μm, [ArIII] 9 μm, [NeII] 12.8 μm, [NeIII] 15.6 and 36 μm, [SIII] 18.7 and 33.5 μm and [SIV] 10.5 μm.

References

[1] Afflerbach, A., Churchwell, E. & Werner, M. W. 1977, *Astrophys. J.* , **478**, 190.

[2] Aller, L.H. 1984, *Physics of Thermal Gaseous Nebulae*, Reidel Publ. Comp.

[3] Black, J.H. & van Dishoeck, E.F. 1987, *Astrophys. J.* , **322**, 412.

[4] Bennett, C.L., Fixsen, D.J., Hinshaw, G., Mather, J.C., Moseley, S.H., Wright, E.L., Eplee, R.E., Gales, J., Hewagama, T., Isaacman, R.B., Shafer, R.A. & Turpie, K. 1994, *Astrophys. J.* , **434**, 587.

[5] Dalgarno, A. & McCray, R.A. 1972, *Ann. Rev. Astr. Astrophys.* , **10**, 375.

[6] Dalgarno, A. 1991, in *Chemistry in Space*, NATO ASI series, eds. J.M. Greenberg and V. Pironello, Kluwer Acad. Publ., p. 71.

[7] Dinerstein, H.L., Lester, D.F. & Werner, M.W. 1985, *Astrophys. J.* , **291**, 561.

[8] Dinerstein, H. 1986, *PASP* , **98**, 979.

[9] Dinerstein, H.L. 1990, in *The Interstellar Medium in Galaxies*, eds. H.A. Thronson and J.M. Shull, Dordrecht: Reidel Publ. Comp., p. 257.

[10] Elmegreen, B.G. 1989, *Astrophys. J.* , **338**, 178.

[11] Federman, S.R., Glassgold, A.E., Jenkins, E.B. & Shaya E.J. 1980, *Astrophys. J.* , **242**, 545.

[12] Field, G.B., Goldsmith, D.W. & Habing, H.J. 1969 *Astrophys. J.* , **155**, L49.

[13] Garnett, D.R. 1992, *Astron. J.* , **103**, 1330.

[14] Genzel, R. 1992, in *The Galactic Interstellar Medium*, Saas-Fee Advanced Course 21, Swiss Society for Astrophysics and Astronomy, eds. D. Pfenniger and P. Bartholdi, Springer Verlag, p. 275.

[15] Herter, T., Helfer, H.L., Forrest, W.J., McCarthy, J., Houck, J.R., Willner, S.P., Puetter, R.C., Rudy, R.J., Soifer, B.T. & Pipher, J.L. 1981, *Astrophys. J.* **250**, 186.

[16] Herter, T., Helfer, H.L., Briotta, D.A., Forrest, W.J. Houck, J.R., Rudy, R.J., Willner, S.P., Pipher, J.L. 1982, *Astrophys. J.* **262**, 153.

[17] Heydari-Malayeri, M. & Testor, G. 1986, *Astr. Astrophys.* **162**, 180.

[18] Israel, F.P. & Koornneef, J. 1991, *Astr. Astrophys.* , **250**, 475.

[19] Kenney, J.D. 1997, in *The Interstellar Medium in Galaxies*, ed. J.M. van der Hulst, ASSL Series, Kluwer Acad. Publ. p. 33

[20] Koornneef, J. & Israel, F.P. 1996, *New Astronomy* , **1**, 271.

[21] Kulkarni, S.R. & Heiles, C. 1987, in *Interstellar Processes*, eds. D.J. Hollenbach and H.A. Thronson, Dordrecht: Reidel Publ. Comp., p. 87.

[22] Kunze, D., Rigopolou, D., Lutz, D., Egami, E., Feuchtgruber, H., Genzel, R., Spoon, H.W.W., Sturm, E., Sternberg, A., Moorwood, A.F.M. & de Graauw, Th. 1996, *Astr. Astrophys.* , **315**, L101.

[23] Lester, D. F., Dinerstein, H. L., Werner, M. W., Watson, D. M. & Genzel, R. 1983, *Astrophys. J.* **271**, 618.

[24] Lester, D. F., Dinerstein, H. L., Werner, M. W., Watson, D. M., Genzel, R. & Storey, J.W.V. 1987, *Astrophys. J.* **320**, 573.

[25] Madden, S.C., Geis, N., Genzel, R., Hermann, F., Jackson, J., Poglitsch, A., Stacey, G.J. & Townes, C.H. 1993, *Astrophys. J.* , **407**, 579.

[26] McKee, C.F. & Ostriker, J.P. 1977, *Astrophys. J.* , **218**, 148.

[27] Megeath, S. T., Herter, T., Gull, G. E. & Houck, J. R. 1990, *Astrophys. J.* , **356**, 534.

[28] Moorwood, A.F.M., Lutz, D., Oliva, E., Marconi, A., Netzer, H., Genzel, R., Sturm, E. & de Graauw, Th. 1996, *Astr. Astrophys.* , **315**, L109.

[29] Okumura, K., Hiromoto, N., Okuda, H., Shibai, H. Nakagawa, T., Makiuti, S. & Matsuhara, H. 1996 *PASJ* , **48**, L123.

[30] Osterbrock, D.E. 1989, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei*, University Science Books, Mill Valley Ca.

[31] Peimbert, M. 1967, *Astrophys. J.* , **150**, 825.

[32] Peimbert, M. & Torres-Peimbert, S. 1977, *MNRAS* , **179**, 217.

[33] Peimbert, M., Storey, P.J. & Torres-Peimbert, S. 1993, *Astrophys. J.* , **414**, 626.

[34] Peimbert, M. 1993, *RMAA* , **27**, 9.

[35] Pipher, J.L., Helfer, H.L., Herter, T., Briotta, D.A., Houck, J.R., Willner, S.P. & Jones, B. 1984, *Astrophys. J.* , **285**, 174.

[36] Pottasch, S.R., Wesselius, P.R. & van Duinen, R.J. 1979, *Astr. Astrophys.* , **74**, L15.

[37] Reynolds, R.A. 1992, *Astrophys. J.* , **392**, L35.

[38] Roelfsema, P.R., Cox, P., Tielens, A.G.G.M., Allamandola, L.J., Baluteau, J.-P., Barlow, M.J., Beintema, D., Boxhoorn, D.R., Cassinelli, J.P., Caux, E., Churchwell, E., Clegg, P.E., de Graauw, Th., Heras, A.M., Huygen, R., van der Hucht, K.A., Hutgins, D.M., Kessler, M.F., Lim, T. & Sandford, S.A. 1009, *Astr. Astrophys.* , **315**, L289.

[39] Rigopolou, D., Lutz, D., Genzel, R., Egami, E., Kunze, D., Sturm, E., Feuchtgruber, H., Schaeidt, S. Bauer, O.H., Sternberg, A., Netzer, H. Moorwood, A.F.M. & de Graauw, Th. 1996, *Astr. Astrophys.* , **315**, L125.

[40] Shibai, H., Okuda, H., Nakagawa, T., Makiuti, S., Matsuhara, H., Hiromoto, N. & Okumura, K. 1996 *PASJ* , **48**, L127.

[41] Simpson, J.P., Bregman, J.D., Dinerstein, H.L., Lester, D.F. Rank, D.M., Witteborn, F.C. & Wooden, D.H. 1995, in *Airborne Astronomy Symposium on the Galactic Ecosystem*, eds. M.R. Haas, J.A. Davidson and E.F. Erickson, ASP Conf. series, **73** p. 105.

[42] Shull, J.M. & Beckwith, S. 1982, *Ann. Rev. Astr. Astrophys.* , **20**, 163.

[43] Sturm, E. Lutz, D., Genzel, R., Sternberg, A., Egami, E., Kunze, D., Rigopolou, D., Bauer, O.H., Feuchtgruber, H., Moorwood, A.F.M. & de Graauw, Th. 1996, *Astr. Astrophys.* , **315**, L133.

[44] Tielens, A.G.G.M. 1995, in *Airborne Astronomy Symposiom on the Galactic Ecosystem*, eds. M.R. Haas, J.A. Davidson and E.F. Erickson, ASP Conf. series, **73**, p. 3.

[45] Tielens, A.G.G.M. & Hollenbach, D.J. 1985, *Astrophys. J.* , **291**, 722.

[46] Tielens, A.G.G.M. & Hollenbach, D.J. 1985, *Astrophys. J.* , **291**, 747.

[47] Valentijn, E.A., van der Werf, P.P., de Graauw, Th. & de Jong, T. 1996, *Astr. Astrophys.* , **315**, L145.

[48] van der Hulst, J.M. 1995, in *Science with the VLT*, eds. J.R. Walsh and I.J. Danziger, Springer Verlag, p. 190.

[49] van Dishoeck, E.F. 1988, in *Millimetre and Submillimetre Astronomy*, eds. R.D. Wolstencroft and W.B. Burton, Kluwer Acad. Publ., p. 117.

[50] Watson, D.M., Genzel, R., Townes, C.H. & Storey, J.W. 1985, *Astrophys. J.* , **298**, 316.