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A new view on the ISM of galaxies: Far-infrared and submillimetre spectroscopy with Herschel

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ABSTRACT

The FIR/submm window is amongst the least explored spectral regions of the electromagnetic spectrum. It is, however, a key to study the general properties of the interstellar medium of galaxies, as it contains important spectral line diagnostics from the neutral, ionized and molecular ISM. The Herschel Space Observatory, successfully launched on 14 May 2009, is the first observatory to cover the entire FIR/submm range between 57 and 672 μm. We discuss the main results from the ISO era on FIR spectroscopy of galaxies and the enormous science potential of the Herschel mission through a presentation of its spectroscopic extragalactic key programs.

1. Introduction: the ISM of galaxies

The ISM of galaxies is not a quiescent medium; it lives in a constant mutual interaction with the stellar component of a galaxy. On the one hand, the ISM is the birthplace of the stars; on the other hand, the stars control the structure and therefore the star formation rate of the ISM. In general, the ISM consists of three distinct phases (components that live in relative thermal pressure equilibrium): a cold, a warm and a hot phase. Dotted between these phases are dense, mainly molecular cores, either collapsing to form stars or expanding due to the feedback of embedded or nearby stars. Most of the mass of the ISM is in neutral regions, either in the cold neutral gas or the molecular clouds. With the exception of the molecular gas deep in the cores of dense star-forming clouds, the physics, chemistry and evolution in these neutral regions is dominated by stellar far-ultraviolet (FUV) photons, with energies between 6 and 13.6 eV. Such regions are generally called photodissociation regions (PDRs). Detailed review papers on the different aspects of PDRs can be found in e.g. Hollenbach and Tielens (1997, 1999).

Not only do PDRs include most of the mass of the ISM in galaxies, they also are responsible for the bulk of the FIR/submm radiation of galaxies. The incident FUV starlight on PDRs is absorbed primarily by dust grains and PAHs. The vast majority of this absorbed energy is re-emitted as FIR/submm continuum radiation or PAH line emission. A minor fraction of the energy, typically 0.1–1%, is converted to energetic photoelectrons, which heat the PDR gas, a process known as photoelectric heating. The gas is less efficient at cooling than the dust and hence reaches higher equilibrium temperatures. It mainly cools through FIR/submm line radiation via atomic fine structure lines and molecular rotation lines.

The first theoretical studies of PDR physics and chemistry in the 1970s concentrated on "obvious" PDR regions such as diffuse clouds or translucent clouds (Glassgold and Langer, 1974; Black and Dalgarno, 1976). Nowadays, PDR studies include a much wider field, including the pervasive warm neutral medium, giant molecular clouds and the ISM in the cores of starburst and/or active galaxies. A plethora of PDR theoretical models have emerged during the past two decades (e.g. Tielens and Hollenbach, 1985; van Dishoeck and Black, 1986; Sternberg and Dalgarno, 1989; Draine and Bertoldi, 1996; Kaufman et al., 1999). PDR models typically are advanced computer codes accounting for a growing number of physical and chemical effects with increasing accuracy. PDR codes simultaneously solve for the relative abundances and level populations of different species, radiative transfer and thermal balance equations in a given geometry. Important ingredients are the grain and PAH properties, the choice of the species in the gas mixtures, the chemical reactions, the heating and cooling mechanisms and the geometry. State-of-the-art codes are now routinely used to make detailed model predictions for observables such as fine-structure line intensities and intensity ratios as a function of the main physical parameters such as the strength of the FUV radiation field and the hydrogen number density (Fig. 1).

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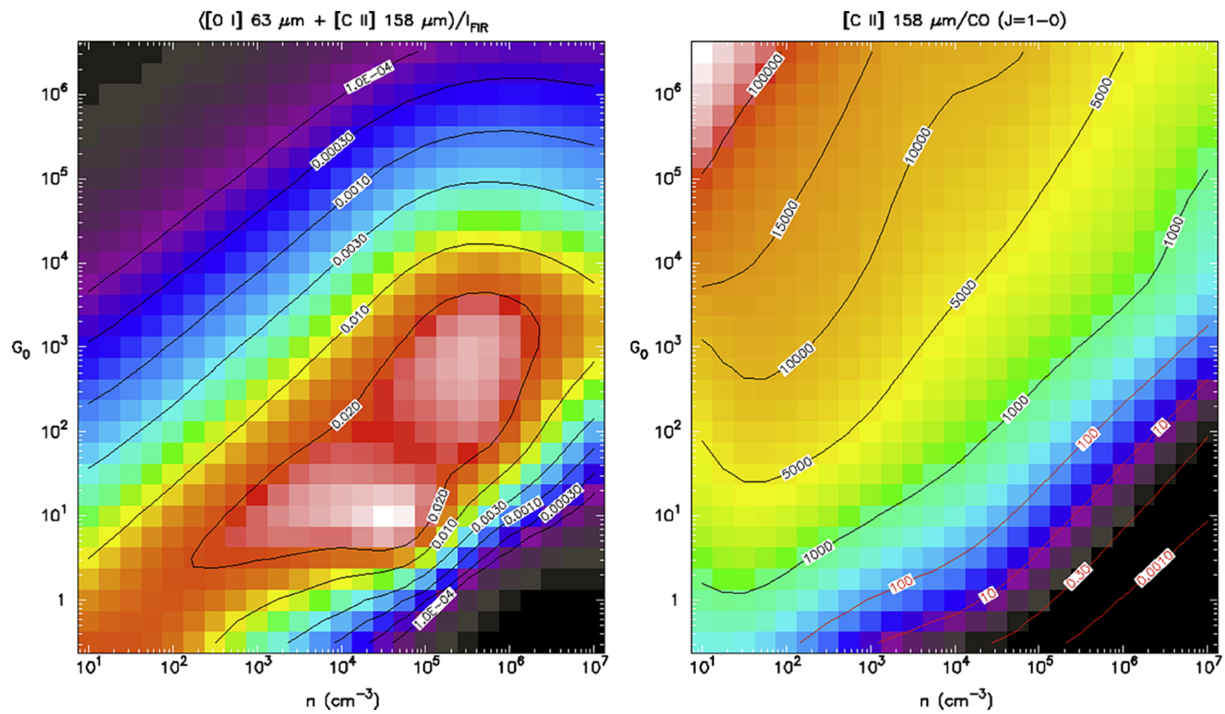

Fig. 1. Theoretical calculation $L_{[CII]+[OI]}/L_{FIR}$ and $L_{[CII]}/L_{CO(1-0)}$ of PDRs as a function of the hydrogen number density and the strength of FUV radiation field falling onto the gas. Figures taken from the PDR Toolbox (http://dustem.astro.umd.edu/pdrt).

From such studies, we can determine the most important cooling lines and create powerful gas diagnostics. While the theoretical PDR models nowadays make detailed predictions of the strengths of all these lines, it is important to be aware of the limitations of these models. Several state-of-the-art numerical PDR codes were recently compared and benchmarked by Röllig et al. (2007). One of the main results was that a significant spread remains between the computed observables, such that caution is needed when comparing astronomical data with PDR model predictions.

2. The far-infrared properties of galaxies

2.1. FIR spectroscopy of nearby galaxies

The first FIR spectroscopic observations were done with KAO, COBE and balloons in the 1980 and early 1990s. A major step forward was the appearance of ISO with its LWS spectrograph, which made studies of large samples of galaxies of different types possible (e.g. Malhotra et al., 1997, 2001; Leech et al., 1999; Negishi et al., 2001).

In agreement with model predictions, the fine-structure line of singly ionized carbon [CII] at 158 μm, is the single most important cooling line of the neutral ISM of normal starforming galaxies (Fig. 2a). Galaxies typically have $L_{[CII]}/L_{FIR}$ in the range 0.1–1%, consistent with PDR models (Fig. 1a). With an ionization energy of 11.2 eV, CII exists mainly in the neutral ISM, but a fraction of the [CII] emission can originate from diffuse ionized regions (Madden et al., 1993; Bennett et al., 1994; Makiuti et al., 2002). Other important fine-structure lines include the [OI] lines at 63 and 145 μm and the [CI] lines at 370 and 609 μm. The [OI] line becomes a more efficient cooling line than [CII] in high-density regions. The ratios of all these different lines can be used to determine the temperature, density, filling factor and FUV radiation field strength.

The FIR spectra of starforming galaxies also contain a number of atomic fine-structure lines that trace ionized gas. The [NII] lines at 122 and 205 μm are good tracers of diffuse low-density ionized gas, whereas the [NIII] line at 57μm and the [OIII] lines at 52 and 88 μm trace the denser ionized gas. Ratios of these lines can be used to derive electron density and the hardness of the UV radiation field.

Finally, the FIR/submm region contains many transitions of molecular lines, including CO, OH, H_2O and CH (Fig. 2b). Molecular line emission originates both in PDRs and in denser molecular cores. The luminosity in the CO(1–0) line is typically three or more orders of magnitude lower than $L_{[CII]}$ for normal starforming galaxies (Fig. 1b).

2.2. Unsolved issues concerning [CII] emission

Somewhat surprisingly, galaxies with higher L_{FIR} and warmer infrared colours have smaller $L_{[CII]}/L_{FIR}$ ratios. In particular, luminous and ultraluminous infrared galaxies show a clear deficiency in [CII] (Luhman et al., 1998; Malhotra et al., 2001). Several explanations have been proposed to explain this trend. The most common explanation is an increased grain charge in galaxies with high levels of FUV radiation, which creates a higher potential barrier to photoelectric ejection and hence reduces the efficiency of the photoelectric heating (Luhman et al., 1998). However, this issue is far from settled: other teams propose other explanations, including an increase in the collisional de-excitation in the [CII] transition at high density (Negishi et al., 2001) or non-PDR contributions to the FIR continuum (Luhman et al., 2003; Curran, 2009).

Another tantalizing discovery by ISO LWS is that low-metallicity galaxies, including both dwarf irregulars and blue low-mass spiral galaxies, often exhibit unusually intense [CII] emission as compared with the 2.6 mm CO(1–0) emission (Mochizuki et al., 1994; Poglitsch et al., 1995; Madden et al., 1997; Smith and Madden, 1997; Madden, 2001). This result may be due to low abundances of dust and heavy elements: in such gas, FUV radiation penetrates more deeply into a molecular cloud, causing a larger CII region relative to the CO core. Alternatively, radiation from diffuse HI clouds may dominate the [CII] emission from these galaxies.

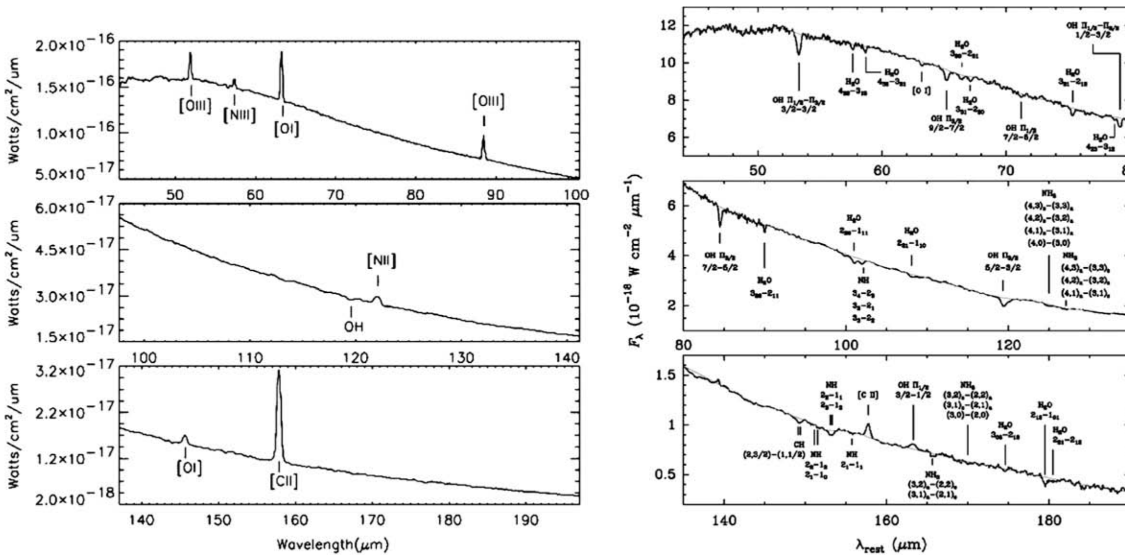

Fig. 2. ISO LWS spectra of M82 (left) and Arp 220 (right). In the starburst galaxy M82, fine-structure emission lines corresponding to both neutral and ionized gas are present Colbert, 1999. The spectrum of the optically thick ULIRG Arp 220 contains many signatures of molecular transitions, as well as [CII] in emission and [OI] in absorption González-Alfonso et al., 2004.

These observations are a strong indication that CO(1–0) measurements are not always a faithful proxy for the molecular gas content.

2.3. Galaxies at high-redshift

In the past decade, submm spectroscopy of galaxies at cosmological distances has seen a spectacular development (Solomon and Vanden Bout, 2005; Omont, 2007). Most of this work was done by the IRAM Plateau de Bure and 30 m telescopes, thanks to both improved detector technology and broader spectral bandwidth which have made the detection of faint extragalactic emission lines with widths of several hundred up to a 1000 km/s possible. Most molecular line studies concentrate on the various transitions of the CO lines, which are our best tracer of molecular hydrogen, and therefore an ideal tracer of the gas reservoirs needed to sustain the prodigious star formation rates implied by their strong far-IR dust continuum emission. The interpretation of CO emission requires observations at various transitions to populate the "CO ladders" and disentangle the temperature and density effects (Weiß et al., 2007) and still limits to densities up to 10^5 cm^{-3}. Other molecular tracers such as HCN have since been detected in the brightest high-redshift objects.

The study of high-redshift objects also allows us to observe the [CII] line from ground-based telescopes. So far, [CII] emission has been detected in one quasar at $z = 6.42$ (Maiolino et al., 2005; Walter et al., 2009) at mm wavelengths and in two systems at $4 < z < 5$ at submm wavelengths (Iono et al., 2006; Maiolino et al., 2009) (Fig. 3a). Particularly interesting is the recent detection of [CII] emission in a lensed system at $z = 4.43$, detected by APEX, which has a superb transmission at submm wavelengths thanks to its location on the Chajnantor plane (the future ALMA site). This

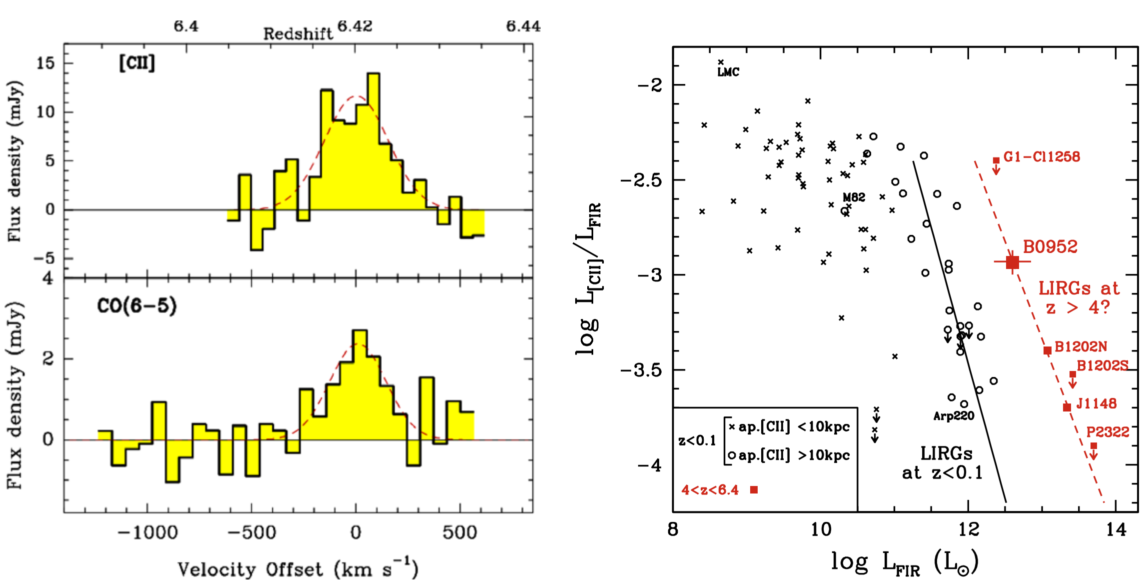

Fig. 3. Left: the detection of [CII] and CO(6-5) emission in a quasar at $z = 6.42$ using the IRAM 30m telescope Maiolino et al., 2005. Right: the $L_{[II]}/L_{FIR}$ ratio versus L_{FIR} for normal and starburst local galaxies (black crosses and circles) and three high-redshift sources (red squares) as in Maiolino et al. (2009).

observation suggests that the [CII] line is brighter than initially assumed, and may be offset from the local $L_{[CII]}/L_{FIR}$ relation (Fig. 3b). This finding remains to be confirmed by future observations, and the physical interpretation is not clear.

3. The promise of Herschel

3.1. The Herschel space observatory

The Herschel Space Observatory, the fourth cornerstone mission in the ESA science programme, was successfully launched on 14 May 2009. With a 3.5 m Cassegrain telescope it is the largest space telescope ever launched. It will perform photometry and spectroscopy in the FIR/submm wavelength range between approximately 55 and 672 μm, bridging the gap between earlier infrared space missions and ground-based facilities. Herschel is the only space facility dedicated to the FIR/submm spectral regime. Its vantage point in space provides several decisive advantages, including a low and stable background and full access to this part of the spectrum.

Herschel has three scientific instruments on board. PACS (Poglitsch and Altieri, 2009) is a camera and low to medium resolution spectrometer for wavelengths in the range between 55 and 210 μm ($R \sim 1500$). SPIRE (Griffin et al., 2009) is a camera and low to medium resolution spectrometer complementing PACS for wavelengths in the range 194–672 μm ($R \lesssim 1000$ at 250 μm). It comprises an imaging photometer and a Fourier Transform Spectrometer (FTS), both of which use bolometer detector arrays. Finally, HIFI (de Graauw et al., 2009) is a very high resolution heterodyne spectrometer covering the 490–1250 GHz and 1410–1910 GHz bands ($R \sim 3 \times 10^6$).

The three instruments are nationally funded (by the ESA member states with contributions from the USA, Canada and Poland).

3.2. Extragalactic FIR spectroscopy with Herschel

The operational lifetime of Herschel is foreseen to be 3 years; about one third of the time is dedicated for guaranteed time observations, two thirds is available for the community through open time. For both guaranteed and open time, a large fraction of the time is used for key programmes (with more than 100 h of observing time). There are five guaranteed time key programs planned on nearby galaxies (one of them only uses submm imaging, the others use a combination of FIR/submm imaging and spectroscopy). The general topic of these proposals is the evolution of the different phases (the stellar, dusty and gaseous phases) within galaxies. The FIR/submm wavelengths probed by Herschel are absolutely crucial for understanding the physical processes and properties of the interstellar medium, the interplay between star formation and the interstellar medium in galaxies, and how they may depend on the wider galaxian environment (See Fig. 4).

The Very Nearby Galaxies (VNG) key program by the SPIRE consortium will use SPIRE and PACS to measure the emission spectrum from dust as well as important cooling lines from the gaseous ISM in sample of 13 very nearby, prototypical galaxies (M51, M81, NGC 2403, NGC 891, M83, M82, Arp 220, NGC 4038/39, NGC 1068, NGC 4151, Cen A, NGC 4125, and NGC 205). These galaxies have been chosen to probe as wide a region in galaxy parameter space as possible while maximizing the achievable spatial resolution and are already well-studied from X-ray and optical through to radio wavelengths. Since the galaxies are well-resolved by the PACS and SPIRE beams, the program will allow to study both variations inside individual galaxies and compare global properties between different galaxies.

Another SPIRE consortium key program will probe the ISM of low metallicity environments. As ISO LWS observations suggest, metallicity can have a profound influence on the ISM structure, on the dust properties, on the radiation field and on the star formation activity. The low-metallicity program will use PACS and SPIRE to map the dust and gas in a 51 dwarf galaxies, sampling a broad metallicity range of 1/50 to 1/3 $Z_\odot$. These data, in conjunction with other ancillary data, will be used to construct the emission spectrum of the dust plus that of the gas in the most important cooling lines. Since low-metallicity dwarf galaxies are the best Local Universe analogs to high-redshift protogalaxies, the interpretation of this data will open the door to comprehending primordial ISM conditions and star formation in the young universe.

The SHINING program is a PACS consortium key program aiming at a FIR spectroscopic and photometric survey of infrared bright galaxies at $0 < z < 1$. The aim is to obtain a comprehensive view of the physical processes at work in the ISM of local galaxies ranging from objects with moderately enhanced star formation to the most dense, energetic, and obscured environments in ultra-luminous infrared galaxies (ULIRGs) and around AGN. The objects cover a wide parameter range in luminosity, activity level, and metal enrichment, and will be complemented by a few objects at intermediate redshifts, i.e. at a more active epoch of star formation. The interpretation of the data will be based on a combination of PDR modelling of the neutral and molecular regions and photoionization modelling of the HII regions.

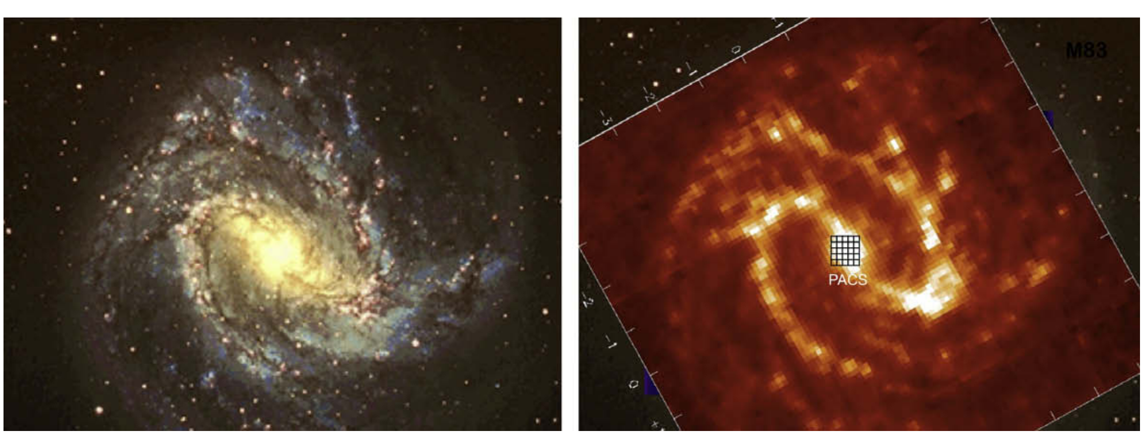

Fig. 4. M83 as an example of a target of the Herschel VNG key program. The left panel shows an optical image, the right panel shows a 7 μm ISOCAM image (Vogler et al., 2005). The FOV and pixel size of the PACS spectroscopy array are also indicated in the right panel. Thanks to the superb resolution, we can investigate the ISM independently in the nucleus, the arm and the interarm regions.

Finally, the HIFI consortium key program called HEXGAL aims at a high spectral resolution submm study of the nuclei of a sample of nearby galaxies (including our own Milky Way). Apart from the key FIR fine-structure lines that will be mapped with PACS, the HEXGAL program focuses on the bright fine-structure lines of atomic carbon, a unique set of water lines, and the high-excitation CO transitions. The multi-line data will be combined with numerical radiative transfer and chemical network models quantitatively constrain the various phases of the ISM.

4. Conclusion

The FIR/submm region is a fascinating wavelength domain that holds the key to study both the neutral, ionized and molecular phases of the ISM. Limited spectroscopic studies so far, mainly based on ISO LWS observations, have already demonstrated the potential of this wavelength region. There is no doubt that the new Herschel mission will revolutionize the study of the ISM of nearby galaxies in terms of sensitivity, spatial and spectral resolution in the coming few years. On a slightly further baseline, ALMA will do a similar job at higher redshift. It will allow us to study the chemistry of the primordial gas in galaxies, which is a strong side constraint on the cosmic evolution of star formation and chemical evolution of galaxies.

References

Bennett, C.L. et al., 1994. ApJ 434, 587.
Black, J.H., Dalgarno, A., 1976. ApJ 203, 132.
Colbert, J.W. et al., 1999. ApJ 511, 721.
Curran, S.J., 2009. A&A 497, 351.
de Graauw, T. et al., 2009. EAS Publications Series 34, 3.
Draine, B.T., Bertoldi, F., 1996. ApJ 468, 269.
Glassgold, A.E., Langer, W.D., 1974. ApJ 193, 73.
González-Alfonso, E., Smith, H.A., Fischer, J., Cernicharo, J., 2004. ApJ 613, 247.
Griffin, M. et al., 2009. EAS Publications Series 34, 33.
Hollenbach, D.J., Tielens, A.G.G.M., 1997. ARA&A 35, 179.
Hollenbach, D.J., Tielens, A.G.G.M., 1999. Reviews of Modern Physics 71, 173.
Iono, D. et al., 2006. ApJ 645, L97.
Kaufman, M.J., Wolfire, M.G., Hollenbach, D.J., Luhman, M.L., 1999. ApJ 527, 795.
Leech, K.J. et al., 1999. MNRAS 310, 317.
Luhman, M.L. et al., 1998. ApJ 504, L11.
Luhman, M.L. et al., 2003. ApJ 594, 758.
Madden, S.C. et al., 1993. ApJ 407, 579.
Madden, S.C., 2001. ASP Conference Series 231, 236.
Madden, S.C., Poglitsch, A., Geis, N., Stacey, G.J., Townes, C.H., 1997. ApJ 483, 200.
Maiolino, R. et al., 2005. A&A 440, L51.
Maiolino, R., et al., 2009. A&A 500, L1.
Makiuti, S. et al., 2002. A&A 382, 600.
Malhotra, S. et al., 1997. ApJ 491, L27.
Malhotra, S. et al., 2001. ApJ 561, 766.
Mochizuki, K. et al., 1994. ApJ 430, L37.
Negishi, T., Onaka, T., Chan, K.-W., Röllig, T.L., 2001. A&A 375, 566.
Omont, A., 2007. Reports on Progress in Physics 70, 1099.
Poglitsch, A. et al., 1995. ApJ 454, 293.
Poglitsch, A., Altieri, B., 2009. EAS Publications Series 34, 43.
Röllig, M. et al., 2007. A&A 467, 187.
Smith, B.J., Madden, S.C., 1997. AJ 114, 138.
Solomon, P.M., Vanden Bout, P.A., 2005. ARA&A 43, 677.
Sternberg, A., Dalgarno, A., 1989. ApJ 338, 197.
Tielens, A.G.G.M., Hollenbach, D., 1985. ApJ 291, 722.
van Dishoeck, E.F., Black, J.H., 1986. ApJS 62, 109.
Vogler, A. et al., 2005. A&A 441, 491.
Walter, F. et al., 2009. Nature 457, 699.
Weiß, A. et al., 2007. A&A 467, 955.