Warm CO Gas and Cold Dust in Galaxies

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Abstract The recent years have seen the 'closing' of the window between radio astronomy and far infrared observations. Several telescopes exist capable of sub-mm wavelength observations, more are under construction. Radio astronomy at cm wavelengths studies thermal (free-free) emissions from hot gas and nonthermal radiation from magnetic fields and relativistic electrons. When we move into the mm wavelengths range we can study many molecular lines as well as emission from cold dust. At sub-mm wavelengths the lines become a forest and the continuum emission comes from warm dust.

1 Introduction

A spectrum of a galaxy at radio wavelengths is made up from contributions of the nonthermal emission that dominates at low frequencies, the free-free emission that is best observed at short cm wavelengths and the dust emission which dominates in the sub-mm wavelength range. A typical spectrum of a galaxy, that for the starburst galaxy M82, is shown in Figure 1. The spectrum in the sub-mm—FIR range can be best fitted by a Planck black-body spectrum with a temperature of $\sim 50\,\mathrm{K}$. The deviation from a one temperature black-body spectrum led observers to fit two or even three temperatures. Superposed on this black-body spectrum we have a great number of spectral lines. The HI line at 1427 MHz and some of the other cm wavelength lines (OH, H_2CO, H_2O, NH_4) make no huge difference to the spectrum. However in the mm and more so in the sub-mm wavelength range a 'forest' of molecular lines comes up that must be taken into consideration in any interpretation. In particular the CO lines contribute a significant flux to the overall spectrum. The 'ladder' of CO lines is given in Table 1. It is to be noted that the higher CO lines require higher temperatures for their excitation. The information can be inverted and from the observation of the line ratios a temperature can be derived. Hence in the sub-mm wavelength astronomy we have a tool to measure the temperature of the dust by continuum (bolometer) measurements and of the CO gas by measuring the transitions. A good review on the background can be found in Hildebrand (1983) or Cox & Mezger (1989). I will concentrate in this talk on the results on nearby galaxies.

Table 1 CO Astronomy

Line	Frequency	T excitation
^{12}CO(1-0)	115.271203 GHz	$\sim 5\,\mathrm{K}$
^{13}CO(1-0)	110.201370 GHz	
^{12}CO(2-1)	230.538001 GHz	$\sim 12\,\mathrm{K}$
^{13}CO(2-1)	220.398714 GHz	
^{12}CO(3-2)	345.79568 GHz	$\sim 35\,\mathrm{K}$
^{12}CO(4-3)	461.04075 GHz	$\sim 55\,\mathrm{K}$
^{12}CO(7-6)	806.65171 GHz	$\sim 120\,\mathrm{K}$
^{12}CO(9-8)	1.03691235 THz	$\sim 150\,\mathrm{K}$

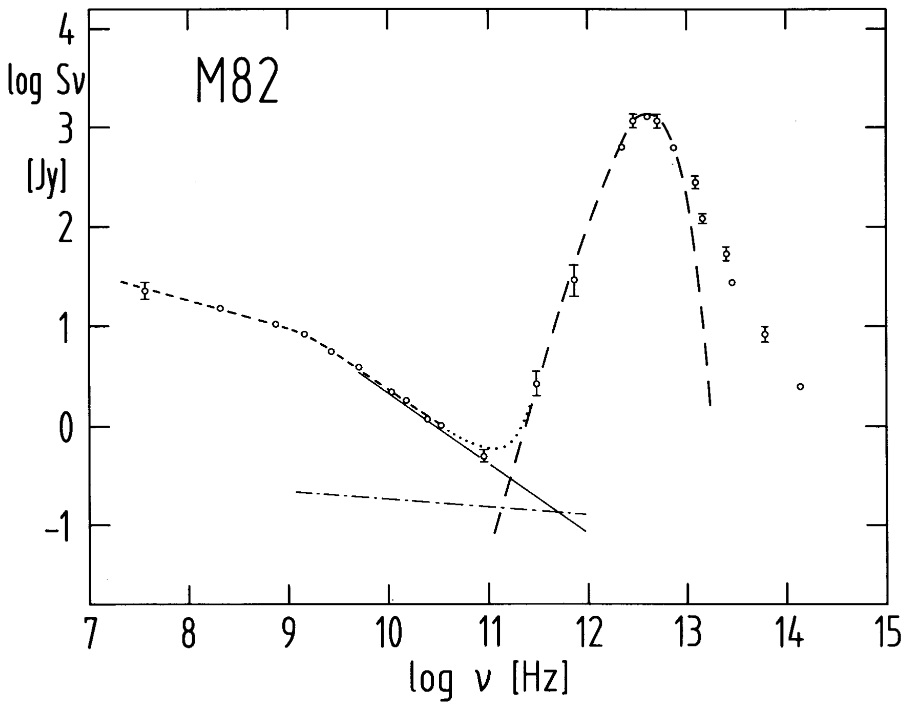

Fig. 1 The spectrum of M82. Below 10^{11} Hz we see nonthermal and free-free radio emission. Above 10^{11} Hz we see dust emission

2 Instruments

The development of this field of research has a long history. The first Galactic CO was detected by Wilson et al. (1970) and extragalactic CO by Rickard et al. (1975) with the 36-ft Kitt Peak NRAO mm-telescope. This NRAO telescope has played a major role in this field of research. Later several new telescopes were constructed, able to work in the mm wavelength range, notably the 13.7 m radome enclosed telescopes of the Five College Radio Astronomy Observatory, the Onsala dish and the Delingha dish. Also the Haystack facility had mm capabilities. The CSO 10.4 m telescope and the 15 m JCMT, placed on the high altitude site in Hawaii contributed lots to the opening up of the higher frequenciy window. The JCMT in particular, equipped with the SCUBA bolometer, became synonymous with continuum (bolometer) observations. The completion of the 30 m Pico Veleta dish of IRAM resulted in a major change in the possibilities to study galaxies in CO(1-0) and CO(2-1) line transitions. Large maps of nearby galaxies became possible with good angular resolution. By now most of the extended nearby galaxies have been mapped. The Pico Veleta telescope was also a major driver in observing red-shifted CO: high line transitions shifted into the lower mm bands. While the Plateau de Bure interferometer was constructed near Grenoble the dish no. 2 was transferred to Chile and became the SEST telescope. Interferometers such as BIMA in the USA contributed a lot of data with good angular resolution. The final instrument in this saga is the 10 m HHT, placed on Mt. Graham, Arizona and operated as the SMTO observatory. This telescope holds the world record in the best surface (rms = 15 μ) and in the highest radio frequency observation made from earth: the detection of the CO(9-8) line in Orion

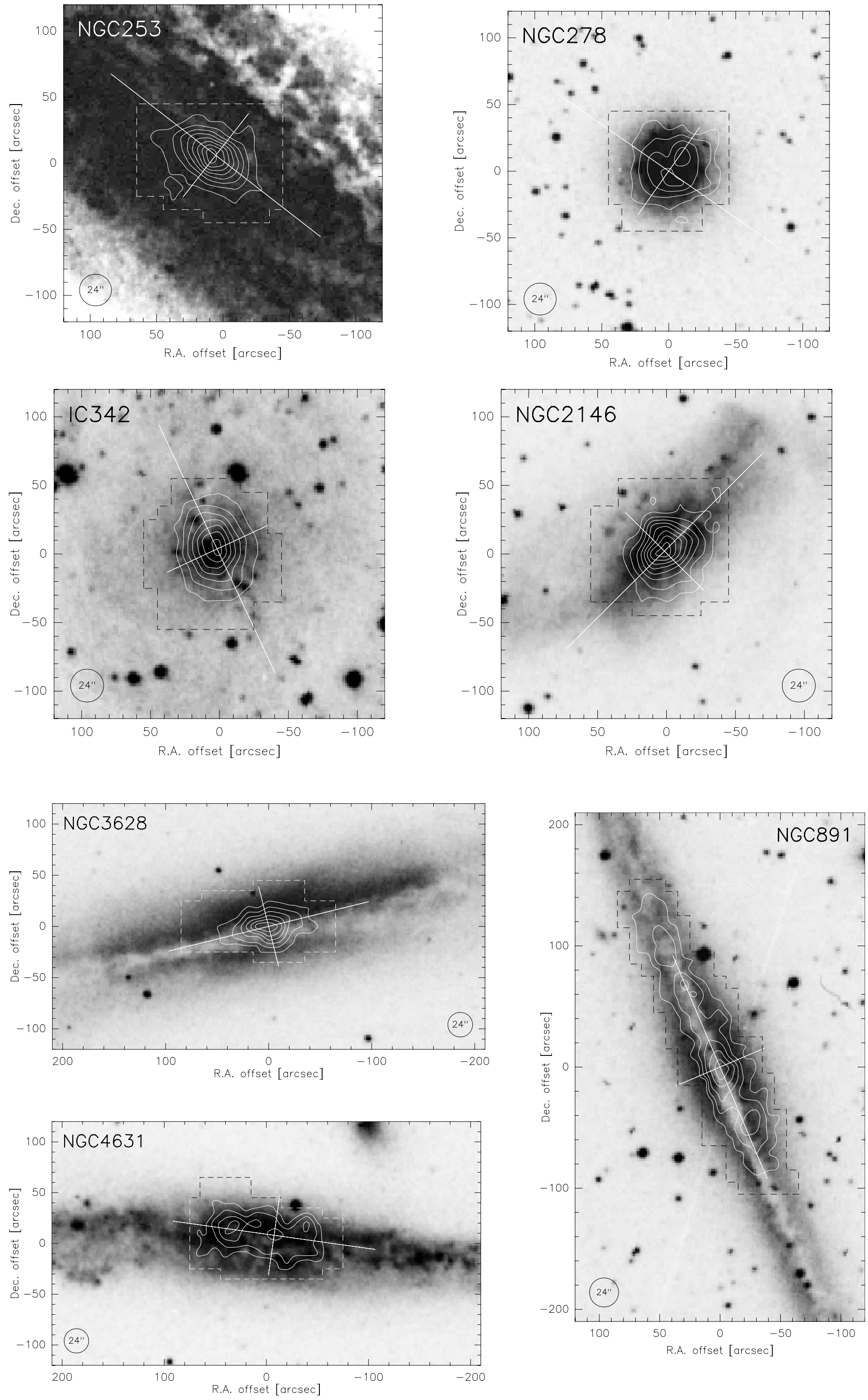

Fig. 2 CO(3-2) Observations of some galaxies

at 1.037 THz. The development of sensitive receivers had to keep up with the telescope developments. All the line receivers are state of art SIS mixers. For continuum observations multi-channel bolometers are needed. The biggest bolometer made at the MPIfR for the Pico Veleta telescope at 1.2 mm wavelength has 117 pixels. The HHT observation at 870 μm are made with a 19-pixel bolometer.

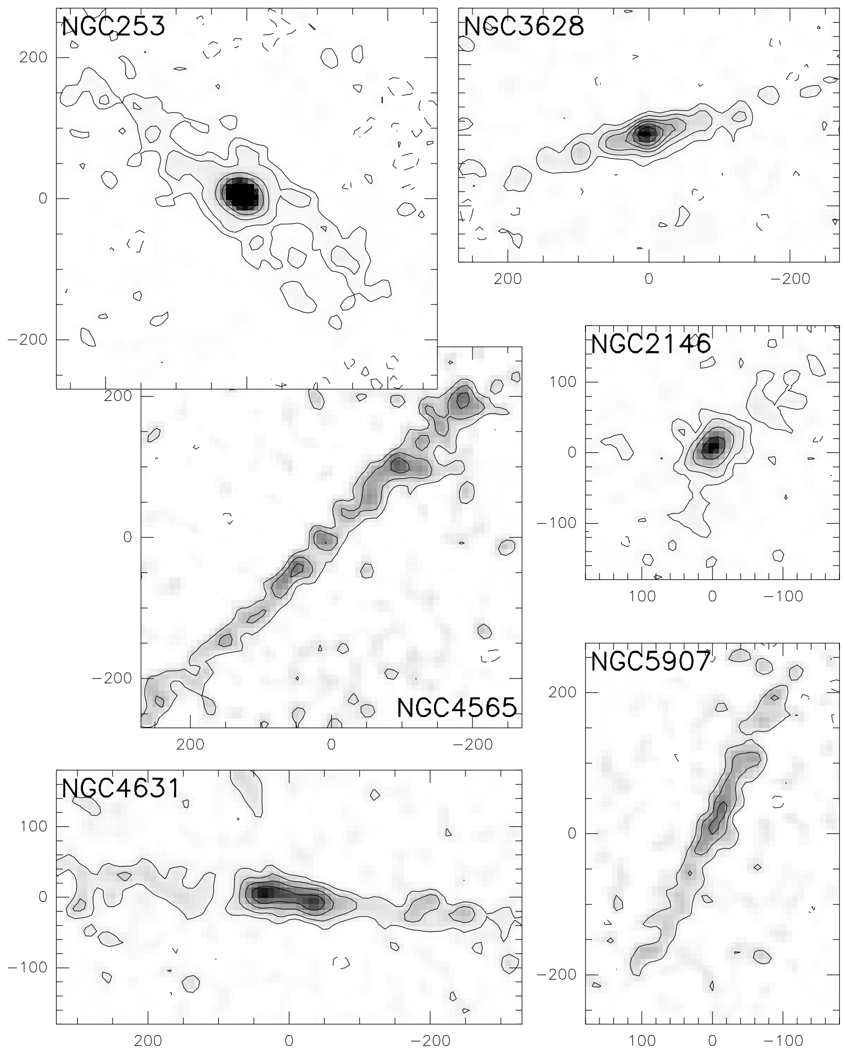

Fig. 3 870 μm observations of some galaxies

3 Our Observations

We have made many of our observations with the Pico Veleta 30 m telescope in the CO(1-0) and CO(2-1) line (e.g. Reuter et al. 1991; Golla & Wielebinski 1994) as well as in $\lambda = 1.2$ mm radio continuum (e.g. Braine et al. 1995; Neininger & Dumke 1999). Some of the studied galaxies were re-observed with better angular resolution with the Plateau de

Bure interferometer. The HHT telescope on Mt. Graham was used to make observations in the CO(3-2) and CO(4-3) lines as well as in $\lambda = 870\,\mu$m radio continuum. The CO data have been published in Wielebinski et al. (1999), Nieten et al. (1999), Dumke et al. (2001) and Walsh et al. (2002). I show a collection of the CO(3-2) results in Figure 2. The bolometer maps, made at $870\,\mu$m, are shown in Figure 3. The combination of all these data allow us to study warm CO gas and cold dust in these galaxies. A surprising result was the discovery of widely distributed warm gas in galaxies. The warm CO gas, with temperatures of 50 K or more is seen over the whole optical image of many galaxies. The dust emission gave some surprising results. The fits showed components with typical temperatures of 20 K and 50 K for most galaxies but needed also the fit of a very cold component with only ~ 5 K in some of the studied objects.

4 The Future

The highest frequency at which a galaxy could be studied at the 3400 m Mt. Graham site was the CO(7-6) line at 806 GHz (Mao et al. 1999). The weather does not permit studies of the higher lines and the shorter continuum wavelengths at either Mt. Graham or Hawaii. As a result of this fact a search for an even better site has been made and the Chajnantor plateau at ~ 5000 m was identified. This site is in the high Andes (Chile) near Antofogasta. This site will be used for the project ALMA, a joint USA-European mm-wavelength interferometer. In anticipation of this development the MPIfR proposed the project APEX, a 12 m pathfinder radio telescope for sub-mm wavelengths to be constructed on the Chajnantor site in Chile at the elevation of 5080 m before ALMA is ready. All the developments at the MPIfR are presently concentrated to make this a successful observatory. Project APEX is a cooperation of the MPIfR with the Bochum University, the Onsala Space Observatory and ESO: the European Southern Observatory that is also the prime leader in the ALMA development.

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References

Braine J, Krügel E, Sievers A. et al, A&A, 1995, 295: L55
Cox P, Mezger P G. A&AR, 1989, 1: 49
Dumke M, Nieten Ch, Thuma G. et al, A&A, 2001, 373: 853
Golla G, Wielebinski R. A&A, 1994, 286: 733
Hildebrand R H. QJRAS, 1983, 24: 267
Mao R Q, Henkel C, Schulz A, et al. A&A, 358, 433
Nieten Ch, Dumke M, Beck R, et al. A&A, 1999, 347: L5
Neininger N, Dumke M. , Proc. Natl. Acad. Sci. USA, 1999, 96: 5360
Reuter H P, Krause M, Wielebinski R, et al. A&A, 1991: 248, 12
Rickard L J, Palmer P, Morris M, et al. ApJ, 1975, 199: L75
Walsh W, Beck R, Thuma G, et al. A&A, 2002, 388: 7
Wielebinski R, Dumke M, Nieten Ch. A&A, 1999, 347: 634
Wilson R W, Jefferts K B, Penzias A A. ApJ, 1970, 161: L43