Dense Molecular Gas in Primeval Galaxies

Simon J. E. Radford

Institut de Radio Astronomie Millimétrique

38406 St. Martin d'Hères, France

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Simon J. E. RADFORD
Institut de Radio Astronomie Millimétrique, 38406 St. Martin d'Hères, France

Abstract

In a sample of ten ultraluminous and normal galaxies, far infrared emission correlates better with the strength of the HCN($1 \to 0$) line than with CO($1 \to 0$). This suggests the star formation efficiency depends on the fraction of the molecular gas reservoir at high density, $n(\mathrm{H_2}) > 10^4\,\mathrm{cm^{-3}}$. The extremely luminous galaxy IRAS 10214+4724 at $z = 2.286$ is tremendously rich in molecular gas. Observations of CO($6 \to 5$), CO($4 \to 3$), and CO($3 \to 2$) indicate the molecular gas is warm and dense, with $n(\mathrm{H_2}) \approx 5000\,\mathrm{cm^{-3}}$ and $T_{\mathrm{kin}} \approx 50\,\mathrm{K}$. The total mass of molecular gas $M(\mathrm{H_2}) = 1 \times 10^{11} h^{-2}\,\mathrm{M_\odot}$. The normal gas to dust mass ratio, 500, indicates the metal abundance is roughly solar. A map of the CO($3 \to 2$) emission shows a small source slightly extended EW. The deconvolved source size of $(8 \times 4) \pm 4h^{-1}$ kpc implies the dynamical mass is $1.3 \times 10^{11} h^{-1}\,\mathrm{M_\odot}$.

1 Dense Molecular Gas in Ultraluminous Galaxies

Rivalling QSOs in emitted power, ultraluminous infrared galaxies ($L_{\mathrm{FIR}} > 5 \times 10^{11} h^{-2}\,\mathrm{L_\odot}$; $H_0 = 100h\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $q_0 = 0.5$) are 3–10 times more common in the local universe ($z < 0.3$) [13]. Almost all show disturbed optical morpholgy: double nuclei, tidal bridges and tails, or other signs of mergers or interactions [9]. Rich in molecular gas, they typically contain $> 5 \times 10^9 h^{-2}\,\mathrm{M_\odot}$ of $\mathrm{H_2}$ [12]. Although some normal spiral galaxies are equally gas rich, e. g. NGC 3147 [19], ultraluminous galaxies have $L_{\mathrm{FIR}}/L_{\mathrm{CO}}$ ratios 30 times higher than do normal galaxies of the same mass [12, 19]. What powers ultraluminous galaxies, obscured black holes in active nuclei or rapid bursts of star formation?

Molecular gas is the raw material for star formation and galactic evolution. The CO($1 \to 0$) line traces gas at $n(\mathrm{H_2}) < 10^3\,\mathrm{cm^{-3}}$ and indicates the total $\mathrm{H_2}$ mass in a galaxy. In ultraluminous galaxies, far IR radiation, emitted by dust warmed by UV radiation from O and B stars, indicates the formation rate of massive stars. The $L_{\mathrm{FIR}}/M(\mathrm{H_2})$ ratio measures, then, the star formation rate per mass of gas, or the star formation efficiency. Why is this efficiency so much higher in ultraluminous galaxies than in normal gas rich spiral galaxies? Does another parameter besides the amount of fuel control star formation in galaxies? In the Milky Way most of the $\mathrm{H_2}$is in low density giant molecular cloud envelopes. Massive stars form, however, not in those envelopes, but in dense cloud cores, objects like M 17, W 51, etc. Although CO traces most of the $\mathrm{H_2}$ mass , it does not necessarily trace the regions of active star formation where the gas density is more than ten times higher than average. Dense molecular gas is better indicated by the HCN($1 \to 0$) line, which traces gas at $n(\mathrm{H_2}) \approx 10^4\,\mathrm{cm^{-3}}$.

In a sample of ten galaxies surveyed with the IRAM 30 m telescope [16], ultraluminous galaxies have much stronger HCN($1\rightarrow0$) lines than normal galaxies. In absolute terms, Mrk 231, the most luminous galaxy in the local universe, has an HCN($1\rightarrow0$) line luminosity larger than the CO($1\rightarrow0$) luminosity of the Milky Way, while in relative terms, Mrk 231 has $L_{\rm CO}/L_{\rm HCN} \approx 4$ whereas $L_{\rm CO}/L_{\rm HCN} \approx 100$ in the Galaxy. For the whole sample, FIR luminosity correlates better with HCN($1\rightarrow0$) luminosity than with CO($1\rightarrow0$) luminosity. Over a range of 50 in $L_{\rm FIR}/L_{\rm CO}$, the range in $L_{\rm FIR}/L_{\rm HCN}$ is only three. When normalized by the CO($1\rightarrow0$) luminosity, there is a very tight correlation between $L_{\rm HCN}/L_{\rm CO}$ and $L_{\rm FIR}/L_{\rm CO}$ (Figure 1). The $L_{\rm HCN}/L_{\rm CO}$ ratio indicates the fraction of the total H_2 mass that has a density $\approx 10^4\,{\rm cm}^{-3}$, i.e. that has conditions necessary for formating massive stars. In any galaxy, ultraluminous or not, the star formation efficiency, measured by $L_{\rm FIR}/L_{\rm CO}$, depends on how much of the total molecular gas is in a dense phase.

2 Warm Molecular Gas in a Primeval Galaxy

With a total luminosity near $10^{14}h^{-2}\,{\rm L}_\odot$, the faint IRAS galaxy 10214+4724 at $z = 2.286$ is as luminous as the strongest QSOs and 20 times more powerful than other known ultraluminous infrared galaxies [11]. It may be a primeval galaxy in an early evolutionary stage. Is this galaxy powered by star formation or by an active nucleus?

Submm continuum emission from 10214+4724 was observed at 450 and 800 μm with the JCMT [4] and at 1.2 mm with the IRAM 30 m telescope [5]. The spectrum (Figure 2) shows the dust is optically thin longward of 175 μm (rest frame). For a ν^2 dust emissivity law, the dust temperature is 80 ± 10 K and the dust mass is $2 \times 10^8 h^{-2}\,{\rm M}_\odot$ [5].

The extraordinary detection of CO($3\rightarrow2$) line emission from 10214+4724 [1] indicates this galaxy has as much molecular gas as the total mass of a large spiral galaxy [18]. There has been, however, some uncertainty about the true line flux. While the original measurement with the NRAO 12 m telescope was 26 Jy km s^{-1} [1], all subsequent measurements with other instruments indicate a much weaker line. A flux of 4.1 ± 0.9 Jy km s^{-1} was observed with the IRAM 30 m telescope (Figure 3) [2, 17], 4.4 ± 0.7 Jy km s^{-1} with the Nobeyama 45 m telescope [20], and 3.5 ± 0.5 Jy km s^{-1} in a map made with the IRAM interferometer (that covers 85% of the total line width) [10]. A higher flux, 7.5 ± 2 Jy km s^{-1}, was measured with the Nobeyama interferometer [7, 14], but within the errors it is consistent with the others (the revised flux quoted for their amplitude calibrator is, moreover, 1.3 times that measured independently with the IRAM 30 m telescope and interferometer). The weighted average of these measurements, 4.3 ± 0.4 Jy km s^{-1}, is six times less than originally reported. Proposed explanations for this discrepancy [2, 7, 14, 20] have invoked additional sources, not coincident with the optical and radio (cm) source, that are outside the primary beams of the 30 m and 45 m telescopes but within the primary beam of the 12 m telescope and *within the fields of view of the interferometers* and that emit 4–5 times more radiation than the central source yet are too extended to be detected by the interferometers. These explanations seem unlikely, however, leaving noise in the original measurement as the likely cause of the discrepancy.

Both CO($4\rightarrow3$) [2] and CO($6\rightarrow5$) [17] have been detected in 10214+4724. In the Milky Way the warm dense gas required for significant excitation of CO($J = 6$) is found only in molecular cloud cores near sites of massive star formation [6]. The measured line ratios in 10214+4724, CO($6\rightarrow5$)/CO($3\rightarrow2$) $= 0.6 \pm 0.2$ and CO($4\rightarrow3$)/CO($3\rightarrow2$) $= 0.8 \pm 0.2$, are considerably higher than overall values for the Milky Way. An LVG radiative transfer calculation shows these ratios are both consistent with $n({\rm H_2}) \approx 5000\,{\rm cm}^{-3}$ and $T_{\rm kin} \approx 50$ K

[17]. This model predicts $CO(3\rightarrow 2)/CO(1\rightarrow 0) = 0.9$ (this ratio is 0.24 in the Galaxy) and $M(H_2)/L_{CO} = 4\,M_\odot\,(K\,km\,s^{-1}\,pc^2)^{-1}$. The $CO(3\rightarrow 2)$ line flux observed with the IRAM 30 m telescope then implies $M(H_2) = 1\times 10^{11}\,M_\odot$ in 10214+4724. The gas to dust mass ratio, 500, is quite normal and suggests the metal abundance is already approximately solar [5].

The distribution of CO in 10214+4724 has been mapped with the Noybeyama [7, 14], Owens Valley [3], and IRAM [10] interferometers. The IRAM map (Figure 4), with $\approx 2''$ resolution, shows a source coincident with the $H\alpha$ [15] and extended 4.85 GHz continuum emission [8]. In two channels $143\,km\,s^{-1}$ apart, there is a shift of $1.4''$ between the positions of maximum emission. After deconvolving the beam, the source size in the integrated map is $(2.5''\times 1'')\pm 1''$ $[(10\times 4)\pm 4h^{-1}\,kpc]$, which together with the linewidth of $240\,km\,s^{-1}$ implies a dynamical mass of $(1.3\pm 0.5)\times 10^{11}\,h^{-2}\,M_\odot$.

The outstanding property of 10214+4724 is its L_{FIR}/L_{CO} ratio, $3000\,L_\odot\,(K\,km\,s^{-1}\,pc^2)^{-1}$, which is 10 times greater than that of other ultraluminous galaxies. If star formation powers this galaxy, then a short starburst of primarily high mass stars in required. The energy available from nuclear burning in $10^{11}\,M_\odot$ of stars indicates star formation can only maintain the luminosity of 10214+4724 for $\approx 10^7$ yr. For a burst of formation of 10 to $100\,M_\odot$ stars, the necessary formation rate is $\approx 3000\,h^{-2}\,M_\odot\,yr^{-1}$, about 5000 times the rate in the Milky Way. A starburst of this magnitude will rapidly enrich the interstellar medium in heavy elements.

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Figure 1: The tight correlation between $L_{\mathrm{FIR}}/L_{\mathrm{CO}}$ and $L_{\mathrm{HCN}}/L_{\mathrm{CO}}$ for both ultraluminous (*solid circles*) and more normal (*open circles*) galaxies suggests the star formation efficiency depends on the fraction of available molecular gas in a dense phase. While $L_{\mathrm{HCN}}/L_{\mathrm{CO}}$ is dimensionless, $L_{\mathrm{FIR}}/L_{\mathrm{CO}}$ is measured in $\mathrm{L}_\odot\,(\mathrm{K\,km\,s^{-1}\,pc^2})^{-1}$ [16].

Figure 2: FIR and submm continuum spectrum of 10214+4724. The sum of an 80 K dust spectrum and a 300 K black body (*solid curve*) fits the measurements while an 80 K black body (*dashed curve*) would produce too much long wavelength radiation [5].

Figure 3: Spectra of $\mathrm{CO}(6\rightarrow5)$ and $\mathrm{CO}(3\rightarrow2)$ emission at $z = 2.286$ from 10214+4724 observed with the IRAM 30 m telescope [17].

Figure 4: IRAM interferometer map of $\mathrm{CO}(3\rightarrow2)$ emission from 10214+4724 at $z = 2.2858$ integrated over $\pm 143\,\mathrm{km\,s^{-1}}$. Contour interval is 1 mJy [10].