Dense Molecular Gas in Ultraluminous and High Redshift Galaxies

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Abstract

Molecular gas is the raw material for star formation and hence a crucial factor in galactic evolution. Ultraluminous infrared galaxies emit the bulk of their power in the far infrared, show disturbed morphologies indicative of recent mergers, and rival QSOs in their bolometric luminosities, but are more numerous in the local universe. Although they are as rich in molecular gas as the most gas rich normal spiral galaxies, they have elevated ratios of infrared luminosity to molecular mass that suggest they are undergoing bursts of very rapid and efficient star formation. A survey of HCN($1 \rightarrow 0$) emission from ten ultraluminous and normal galaxies shows far infrared emission correlates better with the amount of dense, $n(\mathrm{H}_2) > 10^4\,\mathrm{cm}^{-3}$, molecular gas than with the total amount of molecular gas. The star formation efficiency appears to depend on the fraction of the molecular gas reservoir at high density.
The galaxy IRAS 10214+4724 at $z = 2.286$ is perhaps the most luminous object in the universe. Observations of its CO($6 \rightarrow 5$), CO($4 \rightarrow 3$), and CO($3 \rightarrow 2$) lines indicate this galaxy has as much molecular gas as the total mass of the Milky Way. The molecular gas in 10214+4724 is both warmer and denser than that in the Galaxy and the normal gas to dust ratio suggests the abundances are nearly Solar. In the Milky Way, CO($6 \rightarrow 5$) is only observed in regions of high-mass star formation, so its presence in 10214+4724 implies the occurance of active star formation there. A map of the CO($3 \rightarrow 2$) emission with $2.3''$ resolution shows a small source slightly extended EW with a deconvolved size of $(10 \times 4) \pm 4h^{-1}\,\mathrm{kpc}$. The mass of molecular gas is comparable to the dynamical mass. This extraordinary primeval galaxy appears to have most of its mass in molecular gas and to be undergoing an extreme starburst that is generating metals with close to Solar abundances.

1 Dense Molecular Gas in Ultraluminous Galaxies

Rivalling QSOs in emitted power, ultraluminous infrared galaxies ($L_{\rm FIR} > 5 \times 10^{11} h^{-2}\,{\rm L}_\odot$; $H_0 = 100h\,{\rm km\,s^{-1}\,Mpc^{-1}}$, $q_0 = 0.5$) are three times more common in the local universe ($z < 0.3$).[16)] Almost all show disturbed optical morpholgy: double nuclei, tidal bridges and tails, or other signs of mergers or interactions.[12)] Rich in molecular gas, they typically contain[15)] $> 5 \times 10^9 h^{-2}\,{\rm M}_\odot$ of H_2. Although some normal spiral galaxies are equally gas rich, e. g. NGC 3147,[23)] ultraluminous galaxies have $L_{\rm FIR}/L_{\rm CO}$ ratios 30 times higher than do normal galaxies of the same mass.[15, 23)] 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 hence a crucial factor in galactic evolution. The CO($1 \to 0$) line traces gas at $n(H_2) < 10^3\,{\rm cm^{-3}}$ and indicates the total 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 $L_{\rm FIR}/M(H_2)$ 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 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 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 $n(H_2) \approx 10^4\,{\rm cm^{-3}}$.

In a sample of ten galaxies surveyed with the IRAM 30 m telescope,[19)] ultraluminous galaxies have much stronger HCN($1 \to 0$) lines than normal galaxies (Figure 1). In absolute terms, Mrk 231, the most luminous galaxy in the local universe, has an HCN($1 \to 0$) line luminosity larger than the CO($1 \to 0$) 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($1 \to 0$) luminosity than with CO($1 \to 0$) 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($1 \to 0$) luminosity, there is a very tight correlation between $L_{\rm HCN}/L_{\rm CO}$ and $L_{\rm FIR}/L_{\rm CO}$ (Figure 2). 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.

In the most luminous galaxies in the sample, Mrk 231 and Arp 220, the mass of high density gas exceeds $5 \times 10^9 h^{-2}\,{\rm M}_\odot$ and accounts for roughly half the total gas reservoir. In the Milky Way and other normal galaxies, on the other hand, only a small fraction of the gas is sufficiently dense to form high mass stars. The bulk of the molecular gas in the ultraluminous galaxies is, therefore, more similar to that in active star-forming cloud cores than that in the envelopes of GMCs. In our Galaxy, O stars form in massive cloud cores with high density gas and they will form under similar circumstances in ultraluminous galaxies as well. The large masses of high density gas implied by the strength of their HCN($1 \to 0$) lines indicate ultraluminous galaxies are extraordinary star forming environments and suggest star formation is their principal power source. These galaxies are evolving rapidly under conditions reminiscent of those when galaxies formed.

Figure 1: For both ultraluminous (*solid circles*) and more normal (*open circles*) galaxies, FIR and HCN($1\rightarrow0$) luminosity are well correlated.[19)] The upper scale indicates the mass of high density molecular gas, $n(\mathrm{H}_2) \approx 10^4\,\mathrm{cm}^{-3}$. In this Figure, $H_0 = 75\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

Figure 2: The tight correlation between $L_{\mathrm{FIR}}/L_{\mathrm{CO}}$ and $L_{\mathrm{HCN}}/L_{\mathrm{CO}}$ suggests the star formation efficiency of galaxies depends on the fraction of available molecular gas in a dense phase.[19)] While $L_{\mathrm{HCN}}/L_{\mathrm{CO}}$ is dimensionless, $L_{\mathrm{FIR}}/L_{\mathrm{CO}}$ is measured in $\mathrm{L}_\odot\,(\mathrm{K\,km\,s^{-1}\,pc^2})^{-1}$.

2 Warm Molecular Gas in a High Redshift Galaxy

With a total luminosity near $10^{14}h^{-2}\,\mathrm{L}_\odot$, 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.[14)] It may be a primeval galaxy in an early evolutionary stage. Is this galaxy powered by star formation or by an active nucleus?

Submillimeter continuum emission from 10214+4724 was observed at 450 and 800 μm with the JCMT[5)] and at 1.2 mm with the IRAM 30 m telescope.[7)] The spectrum (Figure 3) 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[7)] is $2 \times 10^8 h^{-2}\,\mathrm{M}_\odot$.

The extraordinary detection[1)] of CO($3\rightarrow2$) line emission from 10214+4724 indicates this galaxy has as much molecular gas as the total mass of a large spiral galaxy.[21)] There has been, however, some uncertainty about the true line flux. While the original measurement[1)] with the NRAO 12 m telescope was $26 \pm 6\,\mathrm{Jy\,km\,s^{-1}}$, all subsequent measurements with other instruments indicate a much weaker line (Figure 4). A flux of $4.1 \pm 0.9\,\mathrm{Jy\,km\,s^{-1}}$ was observed with the IRAM 30 m telescope,[3, 20)] $4.4 \pm 0.7\,\mathrm{Jy\,km\,s^{-1}}$ with the Nobeyama 45 m telescope,[24)] and $3.5 \pm 0.5\,\mathrm{Jy\,km\,s^{-1}}$ in a map made with the IRAM interferometer (that covers 85% of the total line width).[13)] A higher flux, $7.5 \pm 2\,\mathrm{Jy\,km\,s^{-1}}$, was measured with the Nobeyama interferometer,[10, 17)] but within the errors it is consistent with the others (the revised flux quoted for the amplitude calibrator is, moreover, 1.3 times that measured independently with the IRAM 30 m

Figure 3: 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.$^{7)}$

Figure 4: Spectra of CO($3 \rightarrow 2$) emission at $z = 2.286$ from IRAS 10214+4724 observed with the NRAO 12 m telescope at 16 MHz resolution,[1)] the IRAM 30 m telescope at 16 MHz resolution (upper;[3)] lower[20)]), the Nobeyama 45 m telescope at 10.5 MHz resolution,[24)] the Nobeyama Millimeter Array at 32.5 MHz resolution (note the spectrum is displayed with twice this resolution, but adjacent channels are not independent),[10, 17)] and the IRAM interferometer (Bure) at 50 MHz resolution.[13)] The $\pm 1\sigma$ error bars represent the per channel uncertainty in each spectrum.

telescope and interferometer). The weighted average of these measurements, $4 \pm 1\,\mathrm{Jy\,km\,s^{-1}}$, is six times less than originally reported. Proposed explanations for this discrepancy[3, 10, 17, 24] 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 hence *within the fields of view of the interferometers* and that emit five times more radiation than the central source yet are too extended to be detected by the interferometers. The only evidence for these extra sources, however, is the large flux seen in the original measurement, which also has the largest uncertainty.

Both $\mathrm{CO}(4\rightarrow3)$[3] and $\mathrm{CO}(6\rightarrow5)$[20] have been detected in 10214+4724 (Figure 5). In the Milky Way the warm dense gas required for significant excitation of $\mathrm{CO}(J = 6)$ is found only in molecular cloud cores near sites of massive star formation.[9] The measured line ratios in 10214+4724, $\mathrm{CO}(6\rightarrow5)/\mathrm{CO}(3\rightarrow2) = 0.6 \pm 0.2$ and $\mathrm{CO}(4\rightarrow3)/\mathrm{CO}(3\rightarrow2) = 0.8 \pm 0.2$, are considerably higher than overall values for the Milky Way. An LVG radiative transfer calculation shows these ratios are both consistent with $n(\mathrm{H_2}) \approx 5000\,\mathrm{cm^{-3}}$ and $T_{\mathrm{kin}} \approx 50\,\mathrm{K}$.[20] This calculation predicts $\mathrm{CO}(3\rightarrow2)/\mathrm{CO}(1\rightarrow0) = 0.9$ (this ratio is 0.24 in the Galaxy) and $M(\mathrm{H_2})/L_{\mathrm{CO}} = 4\,\mathrm{M_\odot}\,(\mathrm{K\,km\,s^{-1}\,pc^2})^{-1}$. Because the temperature of the Cosmic Background Radiation (CBR) should increase as $(1 + z)$, gas at $z \approx 2$ will always have $\mathrm{CO}(3\rightarrow2)/\mathrm{CO}(1\rightarrow0) > 0.5$, even if the density is quite low. The $\mathrm{CO}(3\rightarrow2)$ line flux observed with the IRAM 30 m telescope then implies $M(\mathrm{H_2}) = 1 \times 10^{11}\,\mathrm{M_\odot}$ in 10214+4724. The gas to dust mass ratio, 500, is quite normal and suggests the metal abundance is already approximately Solar.[7]

The distribution of CO in 10214+4724 has been mapped with the Noybeyama,[10, 17] Owens Valley,[4] and IRAM[13] interferometers. The IRAM map (Figure 6), with $2.3''$ resolution, shows a small source coincident with the $\mathrm{H}\alpha$[6, 18] and extended 8.4 GHz continuum emission.[11] The ratio of the intrinsic $\mathrm{CO}(3\rightarrow2)$ brightness temperature derived from the observed line ratios and a radiative transfer calculation, 40 K, and the peak rest frame brightness temperatures measured in the channel maps, 0.7 K, indicates about 1.7% of the synthesized beam area is occupied by radiating gas. A completely filled source of equivalent luminosity would be $0.3''$ in diameter. Despite this low filling factor and the large apparent size of the $\mathrm{CO}(3\rightarrow2)$ emission region, the average surface density, $2500\,\mathrm{M_\odot\,pc^{-2}}$, is ten times higher than for Galactic giant molecular clouds.[22] In two channels $143\,\mathrm{km\,s^{-1}}$ apart, there is a predominantly E-W shift of $1.4''$ between the positions of maximum emission. After deconvolving the beam, the source size in the integrated map is $(2.5'' \times 1'') \pm 1''$ $[(10 \times 4) \pm 4h^{-1}\,\mathrm{kpc}]$. This size scale is characteristic of an entire galaxy, rather than just its nucleus. The velocity gradient implied by the E-W shift suggests the molecular gas is distributed in a rotating structure and the apparent dimensions and aspect ratio further suggest this structure is mostly edge on. For an edge on system with a velocity width of $240\,\mathrm{km\,s^{-1}}$ and a characteristic dimension of 6–$10h^{-1}\,\mathrm{kpc}$, the dynamical mass is 8–$13 \times 10^{10}h^{-1}\,\mathrm{M_\odot}$, which is consistent with the $\mathrm{H_2}$ mass determined from the line flux.

The outstanding property of 10214+4724 is its $L_{\mathrm{FIR}}/L_{\mathrm{CO}}$ ratio, $3000\,\mathrm{L_\odot}\,(\mathrm{K\,km\,s^{-1}\,pc^2})^{-1}$, which is ten 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 $10^{11}\,\mathrm{M_\odot}$ of stars indicates star formation can only maintain the luminosity of 10214+4724 for $\approx 10^7\,\mathrm{yr}$. For a burst of formation of 10 to $100\,\mathrm{M_\odot}$ stars, the necessary formation rate is $\approx 3000\,h^{-2}\,\mathrm{M_\odot\,yr^{-1}}$, about 5000 times the rate in the Milky Way. A starburst of this magnitude will rapidly enrich the interstellar medium in heavy elements.

Figure 5: Spectra of CO(6→5), CO(4→3), and CO(3→2) emission at $z = 2.286$ from 10214+4724 observed with the IRAM 30 m telescope (3, 20)

Figure 6: IRAM interferometer map of CO(3→2) emission from 10214+4724 at $z = 2.2858$ integrated over $\pm 143\,\mathrm{km\,s^{-1}}$. Contour interval is 1 mJy.13)

Figure 7: Predicted intensity of CO($1\rightarrow0$) through CO($6\rightarrow5$) line emission from sources of the same luminosity but different redshifts if observed with the IRAM 30 m telescope in the 3 mm atmospheric window (85–115 GHz). The square symbol indicates the observed CO($3\rightarrow2$) intensity of IRAS 10214+4724. Here $q_0 = 0.5$; if $q_0 = 0.05$ the results are, similiar, although somewhat less favorable for high redshifts. This assumes the intrinsic brightness temperatures are the same for all lines. If the high J lines are not thermalized, they will be, of course, weaker. For this telescope and wavelength, there are $4.5\,\mathrm{Jy\,K^{-1}}$.

3 Further Prospects

Because of the large redshift of IRAS 10214+47624, it's possible to observe several submillimeter spectral lines from the ground that are normally impossible or at least very difficult. A tentative detection of the ($2_{1,1}\rightarrow2_{0,2}$) line of para water has been made with the IRAM 30 m telescope.8) Somewhat surprisingly, the ground state ($1_{1,0}\rightarrow1_{0,1}$) transition of ortho water, which is presumably more abundant, was undetectable with similar sensitivity.

The ${}^3P_2\rightarrow{}^3P_1$ and ${}^3P_1\rightarrow{}^3P_0$ fine structure lines of neutral atomic carbon have been observed with the NRAO 12 m and IRAM 30 m telescopes.2) In the published ${}^3P_2\rightarrow{}^3P_1$ spectrum from the 12 m telescope, there is an apparent emission feature. The center of this feature is, however, displaced by $-350\,\mathrm{km\,s^{-1}}$ from the CO lines. Furthermore, the emission feature coincides with the overlap between data taken with two receiver tunings that were combined without subtracting any baseline. Both transitions were observed with the 30 m telescope, but in neither spectrum are there features as strong as would be expected from the 12 m data if the source were small with respect to the telescope beams. Indeed at the velocities of the strongest feature in the 12 m spectrum, the ${}^3P_2\rightarrow{}^3P_1$ spectrum from the 30 m telescope has a minimum. These measurements remain unconfirmed and controversial.

Because of the difference between angular size distance and luminosity distance,25) spectral lines from high redshift objects are somewhat easier to observe than was first expected.21, 20) Furthermore, for observations in a particular atmospheric window, the CO rotational ladder is convenient since the redshift where a line leaves the lower edge of the band is roughly the same redshift where the next higher transition enters the upper edge of the band. Both because of the increase in the temperature of the CBR with redshift and because we have detected CO($6 \rightarrow 5$) emission from 10214+4724, we expect CO lines up to $J = 6$ should have roughly the same intrinsic brightness temperatures. For objects with the same luminosity as 10214+4724 but at different redshifts, the predicted CO line intensities are almost constant for any $z > 1$ (Figure 7). Current millimeter wave telescopes can detect molecular gas in objects as distant as any known in the Universe.

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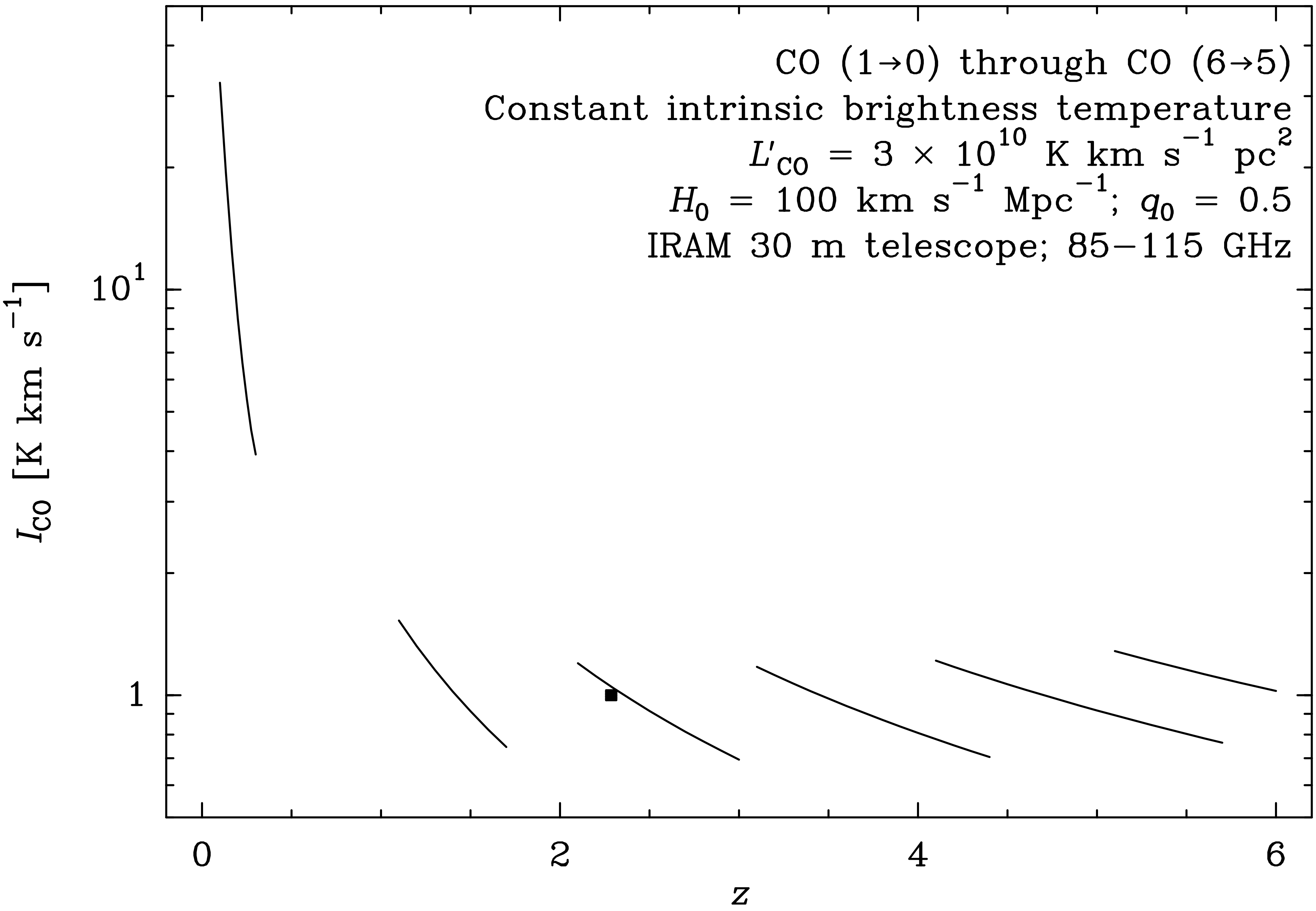
CO (1→0) through CO (6→5)
Constant intrinsic brightness temperature
$L'_{\mathrm{CO}} = 3 \times 10^{10}$ K km s^{-1} pc^2
$H_0 = 100$ km s^{-1} Mpc^{-1}; $q_0 = 0.5$
IRAM 30 m telescope; 85–115 GHz
I_{CO} [K km s^{-1}]
10^1
1
0
2
4
6
z