MOLECULAR LINES AS DIAGNOSTICS OF HIGH-REDSHIFT OBJECTS

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ABSTRACT

Models are presented for CO rotational line emission by high-redshift starburst galaxies. The influence of the cosmic microwave background on the thermal balance and the level populations of atomic and molecular species is explicitly included. Predictions are made for the observability of starburst galaxies through line and continuum emission between \( z = 5 \) and \( z = 30 \). It is found that the Millimeter Array could detect a starburst galaxy with \( \sim 10^5 \) Orion regions, corresponding to a star formation rate of about \( 30 M_\odot \text{ yr}^{-1} \), equally well at \( z = 5 \) or \( z = 30 \) because of the increasing cosmic microwave background temperature with redshift. Line emission is a potentially more powerful probe than dust continuum emission of very high redshift objects.

Subject headings: cosmology: theory — galaxies: evolution — galaxies: starburst — ISM: molecules

1. INTRODUCTION

Searches for CO emission from cosmological objects have had some success. Examples include the IRAS source F10214+4724 at \( z = 2.29 \) (Solomon, Downes, & Radford 1992), the cloverleaf galaxy at \( z = 2.6 \) (Barvains et al. 1994), and a quasar at \( z = 4.69 \) (Omont et al. 1996). These searches establish that large amounts of molecular gas are present at high redshifts. This is to be expected, in the light of the recent detections of high-redshift Lyman break galaxies, e.g., in the Hubble Deep Field, which are actively forming stars at \( z \sim 3–4 \) (Steidel et al. 1996). Since star formation is ultimately driven by the collapse of cold molecular clouds, the occurrence of active star formation must be reflected by the physical structure of the interstellar medium (ISM). The detection of molecular gas and dust at high redshift therefore provides an excellent probe of the stellar processes occurring in cosmological objects. In fact, the metallicity and physical state of the high-redshift ISM provides indirect constraints on the star formation rate and hence on models of galaxy formation.

In the next decade, instruments will come on line to explore the infrared and millimeter regions of the spectrum with the goal of detecting objects at very high redshift: Next Generation Space Telescope (NGST), Far-Infrared and Submillimeter Space Telescope (FIRST), and the Millimeter Array (MMA). The latter will have the ability to detect emission lines fluxes at the millijansky level around wavelengths of a few millimeters and will be ideal for a search for highly redshifted molecular lines, in particular for CO lines. In this work the excitation of the CO molecule will be investigated in the presence of a warm cosmic microwave background (CMB) and the subsequently altered thermal balance. The aim is to determine which molecular lines are best suited for the detection of star-forming primordial galaxies and to assess up to which redshift such measurements are feasible with the planned next generation of observatories.

2. COSMOLOGY

Cosmology does not provide robust predictions for the redshifts of the first galaxies to form. Large-scale structure measurements directly constrain the power spectrum of primordial density fluctuations on scales of \( \sim 5 \) Mpc, or larger, and information on smaller scale power comes from relatively indirect constraints, such as the abundance of high redshift of damped Ly\( \alpha \) absorption clouds. Theory can provide sufficient power to form the first moderately massive galaxies at a redshift as high as 10, and in rare instances at even higher redshift, although popular theories of the cold dark matter variety with nearly scale-invariant primordial power spectra would be hard-pressed to produce many massive galaxies at \( z > 10 \). However, observations are the ultimate arbiter of when galaxies form, and massive galaxies or protogalaxies certainly appear to be present at \( z \sim 5 \).

Moreover, it is generally believed that spheroids are the oldest components of galaxies and formed in an ultraluminous starburst. Such single-starburst models for spheroids are well established by late-time spectral modeling, and at early epochs the lack of success in optical searches for ultraluminous forming galaxies has motivated the inference that spheroids form in ultraluminous dust-shrouded starbursts at high redshift. Observations of nearby ultraluminous infrared galaxies indeed reveal many features in common with the presumed properties of protospheroids. This includes the occurrence of a major merger, a de Vaucouleurs profile in the near-infrared light, a gas surface density and scale size that are comparable to the stellar characteristics of a spheroid, and a star formation rate of several hundreds of solar masses per year (Zepf & Silk 1996; Spaans & Carollo 1997, and references therein). We note parenthetically that there is, however, a rival class of theories, which maintains that most of the stars in spheroids formed in many smaller mergers (Kauffmann & Charlot 1997).

Our best prototype of such luminous starbursts comes from infrared observations, which demonstrate that most of the stellar luminosity is reemitted by dust in the far-infrared (FIR). However, forming spheroids will be extremely gas-rich, and one would expect much of the radiation to be emitted as molecular lines. The cosmic microwave background, we will now show, has a profound influence on the populations of the rotational levels responsible for the strongest lines and leads to
Fig. 1.—Top: Redshift dependence of the column-averaged CO level populations for an Orion region at various redshifts. Note the shift in the peak of the rotational level excitation for higher values of the CMB temperature. Bottom: The corresponding line intensities averaged over the source.

a signature that is potentially detectable out to very large redshift.

3. THE MODEL

A generic starburst galaxy will be assumed to consist of 3 \times 10^5 Orion regions with the model as described in Hogerheijde, Jansen, & van Dishoeck (1995) and Jansen et al. (1995). The strength of the illuminating OB association \( \theta^1 \) Ori is \( L_{UV} = 5 \times 10^4 \) in units of the average interstellar radiation field (Draine 1978). The numerical code developed by Spaans (1996) is used to solve the chemical and thermal balance equations, including the effects of dust attenuation and radiative transfer in the cooling lines of O, C\(^+\), C, Si, Si\(^+\), Fe, Fe\(^+\), and CO. The main features of the code include (1) a three-dimensional inhomogeneous density distribution, (2) heating and cooling processes as described in Tielens & Hollenbach (1985a), (3) a chemical network consisting of 165 species and 648 reactions, and (4) a Monte Carlo treatment of the above radiative transfer effects that incorporates the self-shielding transitions of \( \text{H}_2 \) and CO.

The inhomogeneous density distribution includes a low-density medium of \( 6 \times 10^4 \) \( \text{cm}^{-3} \) with high-density clumps of \( 2 \times 10^6 \) \( \text{cm}^{-3} \) and is taken from the Hogerheijde et al. (1995) model. The clumps contain \( \approx 10\% \) of the material but fill only \( \approx 0.3\% \) of the volume. This distribution provides a good fit to the extensive observations available for the Orion Bar region. For the CO molecule, the level populations are determined in statistical equilibrium with explicit inclusion of the redshift-dependent CMB. All the features of the Galactic Orion region are retained, but various metallicities are considered because these strongly influence the thermal balance and chemical equilibrium. Further details of cosmological applications of the code are provided in Spaans & Norman (1997).

The Orion molecular cloud complex has about \( 5 \times 10^4 \) solar masses in Orion A. Only about 10\% of this mass is in the vicinity of the star-forming region, the Orion Nebula cluster, centered on the Trapezium (Bally et al. 1987). The total FIR (40–300 \( \mu \)m) luminosity of the Orion star-forming region is about 10^5 solar luminosities. This results in a ratio of far-infrared luminosity to molecular gas mass of about 20 \( L_\odot/M_\odot \).

The integrated intensity of all the FIR fine-structure lines is about \( 5 \times 10^{-2} \) ergs \( \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \) at the Trapezium. The integrated FIR continuum intensity at this position is about 12 ergs \( \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \). This yields a photoelectric heating efficiency of about \( 4 \times 10^{-3} \) (Tielens & Hollenbach 1985b).

The main contribution to the high-\( J \) CO lines comes from the so-called Orion Bar region, rather than the molecular cloud, where densities reach \( 10^6 \) \( \text{cm}^{-3} \), sufficient to excite the \( J \leq 10 \) lines in terms of their critical density. This region is less than 1 pc in physical size and will remain beam diluted at any reasonable (\( z < 100 \)) redshift for the MMA with its beam size of 0.1'. In estimating the observed flux, we have incorporated the well-known redshift dependences of surface brightness and angular size diameter.

4. RESULTS AND DISCUSSION

The total molecular gas mass in Orion is about \( 2 \times 10^5 M_\odot \). The star formation rate in Orion is probably about \( 3 \times 10^{-4} M_\odot \text{yr}^{-1} \), according to recent observations of the Orion Nebula cluster (Hillenbrand 1997). Hence our putative protogalaxy containing \( 3 \times 10^5 \) Orions is forming stars at a rate of \( 90 M_\odot \text{yr}^{-1} \) from a gas reservoir of about \( 6 \times 10^{10} M_\odot \). These numbers are merely meant to be representative for a protospheroid of modest mass, amounting to only 10\% or so of the characteristic stellar mass \( M_\star \) (as defined by the galaxy luminosity function) of an elliptical galaxy if the star formation efficiency of the gas is about 50\%. Our results can, of course, be trivially rescaled. The local ratio of FIR luminosity to molecular gas mass of about 20 \( L_\odot/M_\odot \) is in the range associated with luminous starbursts (Sanders, Scoville, & Soifer 1991). This ratio will
Fig. 2.—Redshift dependence of the CO emission spectrum for a starburst galaxy containing $3 \times 10^5$ Orion regions. The gray lines indicate the range in line intensities resulting from metallicities equal to 4 and $1/4$ times solar. Note the rough constancy of the line luminosity with redshift.

vary with location. A more typical value is about half of this, because then the FIR luminosity is inferred to be about $6 \times 10^{11} L_\odot$ and scales appropriately with the global star formation rate for the Milky Way. Hence, our model of $3 \times 10^5$ Orions matches in luminosity, molecular mass, and star formation rate what would be expected from a luminous starburst.

The column-averaged population distribution of CO is shown in Figure 1 (top) as a function of redshift. Line intensities averaged over the source are shown in Figure 1 (bottom). The peak in the level population shifts with increasing redshift to $J = 5-6$, with critical densities $n_c \sim 10^3 \, \text{cm}^{-3}$ and excitation energies of $\sim 80-100 \, \text{K}$ for the corresponding transitions, at $z \sim 30$, before becoming thermalized by the CMB. Note that the line luminosities increase as the CMB becomes hotter because the level excitation increases with increasing $J$ until a CMB temperature $T \sim 90 \, \text{K}$ is attained and higher $J$ lines cannot be pumped in an Orion-like environment because of their high critical density.

The predicted line fluxes are shown in Figure 2. Because of the enhancement of line fluxes by the CMB, we find the remarkable result that beyond $z \sim 5$, the predicted line intensities are almost independent of redshift. Solomon et al. (1992) pre-

Fig. 3.—Redshift dependence of the dust spectrum for the same model as in Fig. 2.
viously noted that the CO ($J = 3–2$) line is always comparable in strength to the CO ($J = 1–0$) line up to $z \sim 2$ because of the warmer microwave background. We find that as higher rotational levels are populated at higher redshift, one can measure a starburst at $z \sim 30$ as easily as at $z \sim 5$. In fact, the measurement may be even easier since the emission peaks at longer wavelengths. The upper and lower gray curves in Figure 2 indicate the range in fluxes for Orion-like regions with metallicities that are 4 times higher and 4 times lower than solar. The overall effect is a factor of a few, which indicates that the effect of the CMB on the CO line intensities is robust.

All lines of interest are in the millimeter range, and the millijansky fluxes predicted for our $3 \times 10^4$ Orion model are within the capability of the MMA to be measurable eventually. Of course, one would have to search a considerable amount of sky. If the duration of a starburst is $\sim 10^8$ yr, and $0.01 \beta$ is the fraction of early-forming elliptical galaxies of mass above $0.1M_\odot$, relative to present-day elliptical galaxies, then one would at most expect $\sim 100 \alpha \beta$ square deg$^{-1}$ at $z \sim 5$, and an order of magnitude fewer at $z \sim 30$.

It is of interest finally to compare the FIR emission with our predicted line fluxes. In Figure 3, we show the continuum fluxes estimated for the Orion dust model. As one proceeds to redshifts above $\sim 5$ the dust emission becomes increasingly harder to detect relative to the line emission. At 100 $\mu$m, the typical continuum flux is about 1 mJy for the $z = 5$ model. It will be a challenge even for FIRST to detect such a weak signal, requiring days of integration. Conversely, the MMA sensitivity limit for spectral lines is expected to be about 1 mJy, as compared to our predicted fluxes of several mJy for our model of what is only, in effect, a modest starburst by ultraluminous infrared galaxy standards.

We comment, in closing, that the main emphasis has been on the rotational lines of CO because of the fortunate energy level spacing for increasing redshifts. Other molecular species such as CS, HCO$^+$, and HCN will be bright emitters as well, but they do not couple as favorably with the CMB. Therefore, their fluxes will be strongly reduced by cosmological redshift effects and not easily detectable at high redshift.

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