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Why Can We Detect the High-Redshift Quasar BR 1202−0725 in CO?

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Abstract

We present CO luminosity evolutions of both elliptical and spiral galaxies based on a galactic-wind model and a bulge-disk model, respectively. We have found that the CO luminosity peaks at around the epoch of the galactic wind caused by collective supernovae ~ 0.85 Gyr after the birth of the elliptical with $M = 2 \cdot 10^{12} M_{\odot}$, while ~ 0.36 Gyr after the birth of the bulge with $M = 2 \cdot 10^{11} M_{\odot}$. After these epochs, the CO luminosity decreased abruptly because the majority of the molecular gas was expelled from the galaxy system as wind. Taking account of typical masses of elliptical galaxies and the bulges of spiral galaxies, we suggest that CO emission can be hardly detected from galaxies with a redshift of $z \sim 1$–4 unless some amplification either by galaxy mergers and/or by gravitational lensing is working. Therefore, our study explains reasonably well why CO emission was detected from the high-redshift quasar BR 1202 − 0725 at $z = 4.7$, while it was not detected from powerful radio galaxies with $1 < z < 4$.

Key words: Cosmology: observations — Galaxies: evolution — Galaxies: formation — Galaxies: nuclei of — Radio lines: CO — Radio sources: AGNs

1. Introduction

The formation and evolution of galaxies are two of the fundamental problems in astrophysics. The recent deep imaging of very faint galaxies made with Hubble Space Telescope (Williams et al. 1996) and the detection of CO emission from a high-z quasar, have encouraged us to study the problem mentioned above. Since galaxies should form from a gaseous system, it is important to investigate the major epoch of star formation in a gas system and to study how stars have been made during the course of galaxy evolution. When we study the evolution of galaxies, we usually use stellar light as the tracer of evolution (cf. Tinsley 1980; Arimoto, Yoshii 1986, 1987; Bruzual, Charlot 1993). However, much data concerning the interstellar medium (ISM) of galaxies from X-ray emitting hot gas through warm H I gas to cold molecular gas and dust have been accumulated during the past decades (cf. Wiklind, Henkel 1989; Lees et al. 1991; Fabbiano et al. 1992; Kim et al. 1992; Wang et al. 1992). Therefore, the time is ripe to begin a study of the evolution of the ISM of galaxies from the epoch of galaxy formation to the present day for both elliptical and disk galaxies.

In this paper, while appreciating the recent detection of CO emission from the high-z quasar, BR 1202 − 0725 (Ohta et al. 1996; Omont et al. 1996), we discuss the evolution of the molecular-gas content in galaxies. Since active galactic nuclei (AGN) are associated with their host galaxies, the CO luminosity of AGN depends on the gaseous content of their host galaxies. Therefore, any observations of molecular-line emission from high-z objects are very useful in studying the evolution of the molecular-gas content in galaxies. In spite of the successful CO detection from BR 1202 − 0725, Evans et al. (1996) reported negative CO detection from 11 high-z ($1 < z < 4$) powerful radio galaxies (PRGs), and gave upper limits on the order of $M_{\mathrm{H}_2} \sim 10^{11} M_{\odot}$ (hereafter $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$), being comparable to or larger than that of BR 1202 − 0725 (Ohta et al. 1996; Omont et al. 1996). Besides the CO detection from BR 1202−0725, there are two more successful detections of CO from high-z objects; 1) the hyperluminous infrared galaxy IRAS F10214+4725 at $z = 2.286$ (Brown, Vanden Bout 1991; Solomon et al. 1992; Tsuboi, Nakai 1992; Radford et al. 1996), and 2) the Cloverleaf quasar H1413 + 135 at $z = 2.556$ (Barvainis et al. 1994). Since, however, these two sources are gravitationally amplified (Elston et al. 1994; Soifer et al. 1995; Trentham 1995; Graham, Liu 1995; Broadhurst, Lehár 1995;

Serjeant et al. 1995; Close et al. 1995), we did not use these data in this study, because there may be some uncertainty in the amplification factor.

Here, a question arises as to why CO emission was detected from the high-z quasar at $z = 4.69$, while not being detected from the high-z ($1 < z < 4$) PRGs. There may be two alternative answers: 1) The host galaxies are different between quasars and PRGs in terms of the molecular-gas contents; 2) although the host galaxies are basically similar between quasars and PRGs, their evolutionary stages are different, and, thus, the molecular-gas contents are systematically different between the two classes. Provided that the current unified model for quasars and radio galaxies (Barthel 1989) is also applicable to high-z populations, it is unlikely that their host galaxies are significantly different. Since it is usually considered that luminous AGNs, such as quasars and PRGs, are associated with either massive ellipticals or the bulges of disk galaxies as well as merger nuclei, the evolution of ISM would be rapidly proceeded during the era of spheroidal component formation. Therefore, we investigate the latter possibility (i.e., evolutionary effect) and discuss some implications concerning the evolution of the ISM in galaxies.

2. Models

Assuming that luminous AGNs are harbored in giant elliptical galaxies and/or in the bulges of spiral galaxies, we investigated the evolution of the CO luminosity (L_{CO}) based on a galactic-wind model for elliptical galaxies proposed by Arimoto and Yoshii (1987) and a bulge-disk model for spiral galaxies by Arimoto and Jablonka (1991). The so-called infall model of galaxy chemical evolution was adopted for both spheroidals and disks; then, time variations of the gas mass and gas metallicity, particularly log(O/H), were calculated numerically by integrating the usual differential equations for the chemical evolution without introducing the instantaneous recycling approximation for the stellar lifetime. Model parameters, such as the star-formation rate (SFR, k), the slope of the initial mass function (IMF, x), and the gas accretion rate (ACR, a), were taken from Arimoto and Yoshii (1987) and Arimoto and Jablonka (1991). The lower and upper stellar mass limits were set to be $m_\ell = 0.1\,M_\odot$ and $m_u = 60\,M_\odot$, respectively.

Jablonka, Martin, and Arimoto (1996) found that the Mg_2–log σ relation of bulges is exactly identical to that of elliptical galaxies. We, therefore, consider that bulges are small ellipticals of equivalent luminosity, and that both spheroidal systems share a similar history of star formation. Thus, for ellipticals and bulges, we assumed that the remaining gas is expelled completely after the onset of a galactic-wind. The wind takes place once the thermal energy released from supernovae exceeds the binding energy of the gas. The wind times, $t_{\mathrm{gw}} = 0.85$ Gyr for giant ellipticals ($M_{\mathrm{init}} = 2 \cdot 10^{12} M_\odot$) and $t_{\mathrm{gw}} = 0.36$ Gyr for bulges ($M_{\mathrm{init}} = 2 \cdot 10^{11} M_\odot$), are taken from Arimoto and Yoshii (1987).

For spiral galaxies, assuming that the bulge and disk evolve independently, we constructed a model by combining the bulge and disk models with $M_{\mathrm{init}} = 2 \cdot 10^{11}\,M_\odot$ and $10^{11}\,M_\odot$, respectively. This model gives $M_V = -20.97$ mag for the bulge and $M_V = -20.87$ mag for the disk at the age of 15 Gyr old (Arimoto, Jablonka 1991). The bulge-to-disk light ratio in the V-band is $L_{\mathrm{b}}/L_{\mathrm{d}} \simeq 1$, nearly twice the typical values for early type spirals (Simien, de Vaucouleurs 1986).

The L_{CO} of a model galaxy can be calculated from the molecular-hydrogen mass by using the empirical CO-to-H_2 conversion factor (X^*). In this paper, L_{CO} refers to that of CO (J = 1–0). Note that the L_{CO} of high-z galaxies are measured by using much higher transitions such as J = 3–2, 4–3, and so on. However, it is known that local CO-rich galactic nuclei and starburst nuclei have $L_{\mathrm{CO}}(J = 3\text{–}2)/L_{\mathrm{CO}}(J = 1\text{–}0) \simeq 1$ (Devereux et al. 1994; Israel, van der Werf 1996). Therefore high-z analogs may have the similar properties. In fact, two high-z objects IRAS F10214 + 4724 and H1413 + 117 have $L_{\mathrm{CO}}(J = 4\text{–}3)/L_{\mathrm{CO}}(J = 3\text{–}2) \simeq 1$ and $L_{\mathrm{CO}}(J = 6\text{–}5)/L_{\mathrm{CO}}(J = 3\text{–}2) \simeq 0.6\text{–}1$ (see table 1 of Israel, van der Werf). Thus, the uncertainty due to using of higher transition data may be 50% at most, when we compare model $L_{\mathrm{CO}}(J = 1\text{–}0)$ and the observed L_{CO} at higher transitions.

Arimoto, Sofue, and Tsujimoto (1995) showed that X^* strongly depends on the gas metallicity, and derived the following relationship, which is valid for nearby spirals and irregular galaxies:

$$\log X^* = -1.0\ (12 + \log \mathrm{O/H}) + 9.30, \qquad (1)$$

where $X^* \times 10^{20}\ \mathrm{H_2/K\ km\ s^{-1}} = N_{\mathrm{H_2}}/I_{\mathrm{CO}}$ and O/H is the oxygen abundance of the H II regions. We introduced a fractional mass of hydrogen molecules to that of atomic hydrogen, $f_{\mathrm{mol}} \equiv M_{\mathrm{H_2}}/M_{\mathrm{H\,I}}$, and wrote the CO luminosity in K km s^{-1} pc^2 as follows:

$$1.6 \cdot X^* \cdot L_{\mathrm{CO}} = M_{\mathrm{H_2}} = M_{\mathrm{H\,I}} \cdot f_{\mathrm{mol}}, \qquad (2)$$

where $M_{\mathrm{H\,I}}$ and $M_{\mathrm{H_2}}$ are in $M_\odot$.

The chemical-evolution model gives $M_{\mathrm{H\,I}}$ and O/H as a function of time, and the CO luminosity evolution can be traced with the help of equation (2), provided that f_{mol} is known *a priori.* We assumed a time-invariant f_{mol} throughout the course of galaxy evolution. In principle, f_{mol} itself should evolve as well, since hydrogen molecules are newly produced on the surface of dust ejected from the evolving stars and/or formed in expanding shells of supernova remnants, while at the same time a part of the molecules are dissociated by UV photons emitted from young hot stars. The mass of the dust and the number of UV photons should also evolve as a result of the galactic chemical evolution (Honma et al. 1995). A detailed evolution of $f_{\rm mol}$ will be discussed in our subsequent paper. Instead, in this paper we assume $f_{\rm mol} = 0.2$. Recent studies of nearby ellipticals suggest $f_{\rm mol} \simeq 0.05$–0.5 (Wiklind, Rydbeck 1986; Sage, Wrobel 1989; Lees et al. 1991; Eckart et al. 1990). Although the contribution of helium to the gas mass is entirely ignored for simplicity, our conclusions change little even if the evolution of helium gas is precisely taken into account.

The formation epoch of galaxies $z_{\rm f}$ is assumed to be 10. Although the choice of $z_{\rm f}$ is rather arbitrary, $z_{\rm f} \geq 5$ has some support from recent studies concerning the metallicity of the broad emission-line regions of high-z quasars (Hamann, Ferland 1992, 1993; Kawara et al. 1996; Taniguchi et al. 1997).

3. Results

3.1. CO in Ellipticals

Figure 1 shows the result for elliptical galaxies. The thick solid line represents the galactic-wind model, and the dotted line is for a model with continuous star formation (the wind is suppressed even after the wind criterion is satisfied). The dashed line shows the case for a wind model; however, the gas ejected from evolving giants after the wind is bound and accumulated in the galaxy to form neutral gas (bound-wind model; Arimoto 1989). The CO luminosity of elliptical galaxies increases prominently soon after their birth, and attains the maximum at an epoch of about 0.85 Gyr, since the birth, or at $z \simeq 4$. Then, it suddenly decreases when the galactic wind has expelled the ISM from the galaxy.

The extremely luminous phase in CO observed for the high-z quasar BR 1202 − 0725 (Ohta et al. 1996; Omont et al. 1996) can be well explained if it is in the star-forming phase of the whole elliptical system. Moreover, the non-detection of smaller redshift galaxies, as observed by Evans et al. (1996), and van Ojik et al. (1997) can also be naturally understood using the present model. This is because of the fact that elliptical galaxies at $z < 4$ contain little ISM.

In the figure, we also superpose CO observational data for lower redshift elliptical galaxies (Wiklind, Rydbeck 1986; Sage, Wrobel 1989; Wiklind, Henkel 1989; Eckart et al. 1990; Lees et al. 1991; Sage, Galletta 1993; Sofue, Wakamatsu 1993; Wiklind et al. 1995). The theoretical curve for the bound-wind model is clearly inconsistent with the observations for galaxies at $z < 0.1$. This suggests that the gas has been expelled continuously after the galactic wind ($z \simeq 4$), and has not been bound to the system. This, in turn, is consistent with the idea that the intracluster hot gas with high metallicity, as observed in X-rays, may have been supplied by the wind from early-type galaxies (Ishimaru, Arimoto 1997). Although it has not been clarified how the gas was expelled out of the galaxies, without being bound to the system, recent studies suggest that it was probably due to the energy supply from either type-Ia supernovae (Renzini et al. 1994) or intermittent AGN activities.

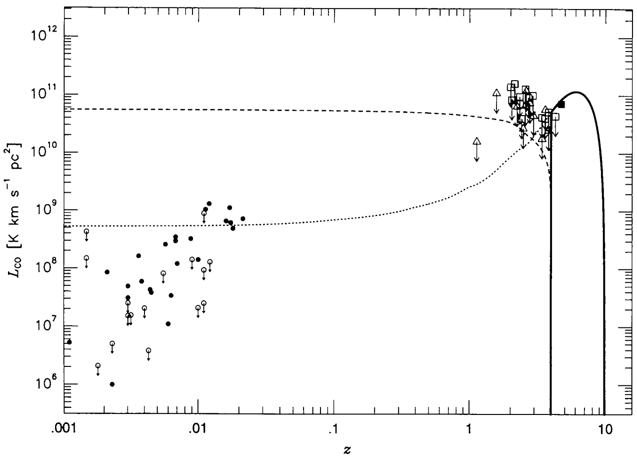

Fig. 1. CO luminosity evolution for elliptical galaxies. The thick solid line represents the galactic wind model; $M_{\rm G} = 2 \cdot 10^{12} M_{\odot}$, $k = 10$ Gyr^{-1}, $x = 1.10$, $a = 10$ Gyr^{-1}, $t_{\rm gw} = 0.85$ Gyr, and $z_{\rm f} = 10$. The dotted line gives a model with continuous star formation and the dashed line shows a case for bound-wind model. A filled square and a filled pentagon shows the observed $L_{\rm CO}$ of the high-z quasar BR 1202 − 0725 (Ohta et al. 1996). Open triangles and open squares indicate the upper limits of negative detection from high-z radio galaxies by Evans et al. (1996) and van Ojik et al. (1997). Filled circles show the $L_{\rm CO}$ of nearby ellipticals (Wiklind, Rydbeck 1986; Sage, Wrobel 1989; Wiklind, Henkel 1989; Eckart et al. 1991; Lees et al. 1991; Sage, Galletta 1993; Sofue, Wakamatsu 1993; Wiklind et al. 1995) and open circles give the upper limits for non-detected elliptical galaxies (Sofue, Wakamatsu 1993; Wiklind et al. 1995). After our paper was submitted, Scoville et al. (1997) reported the CO emission from a weak radio galaxy 53W002 ($z \simeq 2.38$) . The $L_{\rm CO}$ is around $3.98 \cdot 10^{10}$ K km s^{-1} pc^2 adopting the cosmology used here.

3.2. CO in Spirals

Figure 2 shows the result for a spiral galaxy, where the initial masses of the bulge and disk are taken to be $2 \cdot 10^{11} M_{\odot}$ and $10^{11} M_{\odot}$, respectively. The CO luminosity of the bulge evolves in almost the same fashion as an elliptical galaxy as above: the $L_{\rm CO}$ increases rapidly after the birth, attains the maximum within 0.36 Gyr, and, then, suddenly decreases because of the strong wind from the star-forming bulge. The CO luminosity of the thus-calculated forming bulge seems to be insufficient to be detected as the observed luminosity of BR 1202 − 0725,

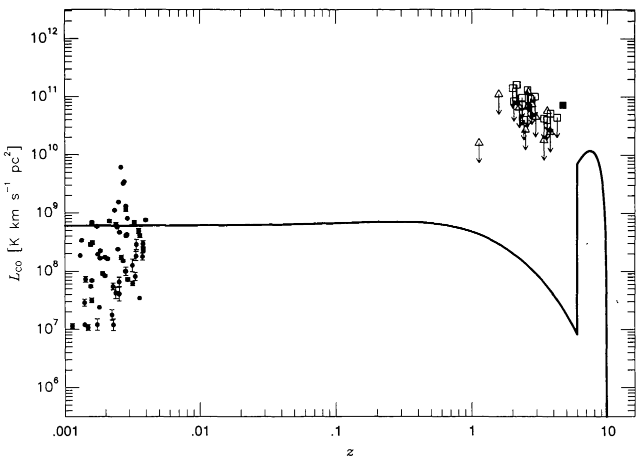

Fig. 2. CO luminosity evolution for spiral galaxies. The thick solid line represents the bulge-disk model; $M_G = 2 \cdot 10^{11} M_{\odot}$, $k = 0.32$ Gyr^{-1}, $x = 1.45$, $a = 0.17$ Gyr^{-1}, and $z_f = 10$ for the disc and $M_G = 10^{11} M_{\odot}$, $k = 10$ Gyr^{-1}, $x = 1.10$, $a = 10$ Gyr^{-1}, $t_{gw} = 0.36$ Gyr, and $z_f = 5$ for the bulge. A filled square, a filled pentagon, open triangles, and open squares are the same as in figure 1. Small filled circles give the L_{CO} of nearby spiral galaxies taken from Braine et al. (1993).

unless the bulge is much heavier than $2 \cdot 10^{11} M_{\odot}$. Moreover, we emphasize that the duration of this bright phase in L_{CO} is shorter than that obtained for ellipticals by a factor of two, and, therefore, the probability to detect such a CO-bright phase for a bulge would be much smaller than that for elliptical galaxies.

On the other hand, the formation of a gaseous disk due to gas infall and star formation then proceeds mildly, and, therefore, the metal pollution of ISM in the disk is slower, which results in a slower increase of the CO luminosity. As a consequence, the CO luminosity has increased gradually and monotonically until today. Also, the less-luminous phase due to the disk, following the wind phase of the bulge, is in agreement with the upper-limit observations of Evans et al. (1996) and van Ojik et al. (1997).

We also plot the CO observations for other nearby spiral galaxies, as plotted by filled circles (Braine et al. 1993). The evolution of the CO luminosity of these galaxies can be traced back by adjusting the present-day luminosity of the calculated track. The most luminous nearby spirals in CO is NGC 4565 ($L_{CO} \simeq 6 \cdot 10^{9}$ K km s^{-1} pc^{2}). It is interesting to mention that, if the model is normalized to this galaxy, the peak CO luminosity corresponding to the forming bulge phase can still be sufficient to explain the luminosity of BR 1202 − 0725.

4. Discussion

The present study has shown that the current radio-telescope facilities are capable of detecting CO emission from high-redshift galaxies which experience their initial starbursts if the following two conditions are satisfied: 1) the masses of the systems should exceed $\sim 2 \cdot 10^{12} M_{\odot}$, and 2) their evolutionary phases should be prior to the galactic wind. Therefore, the detectability of CO emission from high-z galaxies is severely limited by the above two conditions. Our study suggests that CO emission can be hardly detected from galaxies with redshifts of $z \sim 1$–4 without any amplification by either galaxy mergers and/or by gravitational lensing. This prescription is consistent with the observations: CO emission was detected from the high-redshift quasar BR 1202 − 0725 at $z = 4.7$ (Ohta et al. 1996; Omont et al. 1996) while it was not detected from radio galaxies with $1 < z < 4$ (Evans et al. 1996; van Ojik et al. 1997) and quasars with redshift ~ 2 (Takahara et al. 1984). Further, the two convincing detections of CO emission from the high-z objects at $z \sim 2$, IRAS F10214 + 4724 (cf. Radford et al. 1996) and the Cloverleaf quasar H1413+135 (Barvainis et al. 1994), are actually gravitationally amplified sources.

The striking non-detection of high-z galaxies in CO at $1 < z < 4$ implies that most elliptical galaxies and bulges of spiral galaxies were formed before $z \sim 4$, or high-z galaxies with $1 < z < 4$ observed in the optical and infrared studies may be galaxies after the epoch of galactic wind. This implication is consistent with the formation epoch ($z > 4$) of high-z quasars studied based on the chemical properties of the broad emission-line regions (Hamann, Ferland 1992, 1993; Hill et al. 1993; Elston et al. 1994; Kawara et al. 1996; Taniguchi et al. 1997). Therefore it is strongly suggested that most host galaxies of high-z AGNs were formed before $z \sim 4$.

According to our model, it would be worth noting that quasar nuclei are hidden by dusty clouds unless the galactic-wind could expel them from the host galaxies. We also mention that quasar nuclei are not necessarily to associate with a gas-rich circumnuclear environment, though this implication does not contradict what was suggested for low-z AGN (Yamada 1994). Therefore, it seems very lucky that the CO emission was detected from BR 1202 − 0725 at $z = 4.69$.

Finally, we revisit the important question: What is BR 1202−0725? As shown in section 3, the unambiguous CO detection from BR 1202−0725 is interpreted as being an initial starburst galaxy which is forming either an elliptical or a bulge with a mass larger than $\sim 2 \times 10^{12} M_{\odot}$. The elongated (Ohta et al. 1996) or the double-peaked (Omont et al. 1996) CO distribution may be understood as being possible evidence for a galactic wind in terms of our scenario. If it is an elliptical galaxy, its formation epoch is estimated to be $z_f \sim 5$–10. However, if it were to be a bulge former, the mass of bulge should be comparable to that of typical ellipticals. Since such massive bulges are rarer by two orders of magnitude than ellipticals with similar masses (e.g., Woltjer 1990), the host of BR 1202 − 0725 may be an elliptical from a statistical point of view.

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