Dust and molecular gas in high redshift radio galaxies

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Abstract

This review discusses the current status of our knowledge of emission by dust and molecular gas in high redshift radio galaxies, and the uncertainties in the derivation of physical parameters from these data. The similarity of far-infrared luminous, gas-rich high redshift radio galaxies and local ultraluminous infrared galaxies (ULIGs) is discussed. Given that local ULIGs rapidly convert most of their gas reservoir into stars, far-infrared luminous high-$z$ radio galaxies are likely undergoing immense bursts of star formation, possibly accounting for a large fraction of the final stellar populations in these systems. These results are discussed in the context of formation scenarios of massive galaxies.

1 Introduction

In recent years, evidence has been accumulating that radio galaxies at various redshifts can be used to trace the formation and evolution of massive elliptical galaxies. At low redshift, it has long been known that that radio-loud active galactic nuclei (AGNs) are found predominantly in luminous ($L \sim 2-5 L_*$) elliptical galaxies, which are often the dominant cD galaxies of rich clusters (e.g., Matthews et al. 1964). At $z \sim 1$, the host galaxies of well-studied 3CR sources are fully formed massive ellipticals (Best et al. 1998a). High redshift ($z > 2$) radio galaxies on the other hand, show a variety of morphologies, which is often characterized by the presence of a number of clumps (e.g., Miley et al. 1992; Pentericci et al. 1997), totally unlike the more relaxed appearance of their lower $z$ counterparts. The properties of these high-$z$ radio galaxies likely reflect...
processes related directly to the buildup of the bulk of the stellar population. Hence the formation of present-day massive ellipticals may be observed directly in high-\(z\) radio galaxies.

The purpose of this review is to address the implications of the recent detections of dust emission in a number of high-\(z\) radio galaxies for our understanding of the role of these objects in the formation and early evolution of massive galaxies. After a description of the general observational and theoretical context (Sect. 2), the present observational situation in this rapidly developing field is reviewed (Sect. 3). These results are then discussed in the context of what we know about far-IR luminous galaxies in the local universe (Sect. 4). Throughout this paper we adopt a value \(H_0 = 75\) km s\(^{-1}\) Mpc\(^{-1}\) for the Hubble constant, and a deceleration parameter \(q_0 = 0.1\), unless otherwise indicated. Where necessary, results from other publications are tacitly converted to the cosmology adopted here.

## 2 Formation scenarios of massive galaxies

It is convenient for the purpose of this review to divide galaxy formation scenarios into two types.

1. **Hierarchical clustering** scenarios emphasize the gradual buildup of massive objects from initially smaller fragments as the main driver of the evolution of the galaxy population (e.g., White & Frenk 1991; Kauffmann et al. 1993; Baugh et al. 1998).

2. The **monolithic collapse** scenario is based on the idea that an initial starburst occurs, in which a galaxy forms the bulk of its stellar population in a short amount of time; during this starburst, most of the baryonic mass of the galaxy is turned from gas into stars.

It should be emphasized from the outset, that these two scenarios are not as diametrically opposed as they seem. For instance, in the hierarchical clustering scenario, a major merger is required to form an elliptical galaxy. In the local universe, such major mergers are known to be accompanied by intense starbursts, as observed in the ultraluminous infrared galaxies (ULIGs), in which a large fraction of the available gas reservoir is rapidly converted into stars. Therefore, even though they are not currently “forming”, the local ULIGs possess all the properties of a massive galaxy building up its stellar population by monolithic collapse. Thus even within the framework of hierarchical merging, galaxies that behave as if they are undergoing monolithic collapse exist.
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Since the monolithic collapse scenario would result in a galaxy, the stellar component of which is dominated by an evolved population, this scenario has been applied mostly to the formation of spheroids. The recent discoveries of luminous (up to a few times $10^{14} \, L_{\odot}$) far-IR emission and large amounts of dust and molecular gas in a number of high-z quasars and radio galaxies (e.g., Dunlop et al. 1994; McMahon et al. 1994; Ohta et al. 1996; Omont et al. 1996a,b; Guilloteau et al. 1997) are directly relevant in this context. With their high far-IR luminosities, large dust masses and large (inferred) molecular gas masses, these distant objects seem to be the more extreme high-z counterparts of the local ULIGs. While the AGNs in the high-z far-IR luminous objects contribute an unknown fraction to the powering of the far-IR luminosity, this argument only changes the conclusion qualitatively, since it would be extremely surprising if intense star formation were not taking place in such immense agglomerations of gas and dust; furthermore, many local ULIGs also possess an AGN contributing to the far-IR luminosity. Since dust emission has now been found in a number of high-z radio galaxies, such objects may turn out to be Rosetta stones for understanding the formation of massive galaxies.

Given these results it is important to examine the view that these far-IR luminous high-z objects can indeed be regarded as forming by monolithic collapse. The expected parameters for such objects can be estimated by considering a gas mass $M_g$ collapsing and forming stars on a free fall timescale $t_{ff}$, resulting in a star formation rate $\dot{M}_* = M_g / t_{ff}$. Starting with an isothermal sphere, the resulting star formation rate is

$$\dot{M}_* \, M_{\odot} \, yr^{-1} = 40 \left( \frac{v_c}{100 \, km \, s^{-1}} \right)^3,$$

where $v_c$ is the circular velocity, which can be related to the enclosed mass $M$ within radius $R$ using

$$v_c^2 = \frac{GM}{R}.$$

The monolithic collapse scenario will be a valid approach if the buildup of the initial starburst occurs on a timescale shorter than that of merger-driven evolution. As shown by Eqs. (1)–(2), this condition will be fulfilled in the most massive systems, which have the highest star formation rates. Indeed, star formation rates estimated for far-IR luminous high-z galaxies are among the highest derived for any object in the universe, consistent with the present approach of analyzing these objects as galaxies forming by monolithic collapse.
A dusty starburst galaxy emits more than 90% of its luminosity in the far-IR wavelength region. The thermal dust emission obeys the relation $S_\nu \propto Q_\nu B_\nu(T_d)$, where $B_\nu(T_d)$ is the Planck function at the dust temperature $T_d$, and $Q_\nu$ is the dust emissivity, which in the submillimetre region obeys the relation $Q_\nu \propto \nu^\beta$, with $\beta$ increasing with wavelength from 1 to 2. Therefore, in the long wavelength Rayleigh-Jeans regime, the thermal dust emiss ion falls off as $S_\nu \propto \nu^{-4}$. Hence for dusty high-$z$ objects, where the peak of the thermal dust emission is shifted into the (sub)millimetre regime, a very large, negative $K$-correction applies. As a result, the (sub)millimetre regime is the ideal spectral region for studying dusty high-$z$ starburst galaxies. This statement is illustrated by Fig. 1, which shows that the observed 850\,$\mu$m flux of a galaxy with the far-IR spectral energy distribution (SED) of Arp 220 does not decrease as the redshift increases from 1 to 10. For the adopted cosmology, Arp 220 would have an 850\,$\mu$m flux density of about 3\,mJy in this redshift range, a value within reach of the most sensitive present-day submillimetre facilities such as the Submillimetre Common User Bolometer Array (SCUBA) at the 15\,m James Clerk Maxwell Telescope (JCMT). Figure 1 furthermore shows that given a submillimetre detection of a galaxy of unknown redshift, any redshift between...
1 and 10 is equally likely. Finally, it can be seen that even in the absence of an accurate redshift determination, the far-IR luminosity can be reasonably well estimated, provided the redshift is between 1 and 10. As shown by Blain & Longair (1993), a deep submillimetre-selected sample will contain a very high proportion of high-z galaxies. These properties are unique to the submillimetre region and make this spectral interval the ideal regime for studying star formation in the high-z universe.

Before examining submillimetre observations of high-z radio galaxies, it is useful to analyse the assumptions and uncertainties in the derivation of physical quantities from the observational results. The quantities of most fundamental importance of the star formation rate $\dot{M}_*$ and the molecular gas mass $M_{\rm H_2}$. Since the latter quantity is sometimes derived from the dust mass $M_d$, this quantity will also be discussed.

- The star formation rate $\dot{M}_*$ is readily derived from the far-IR luminosity $L_{\rm FIR}$, using

$$\frac{\dot{M}_*}{M_\odot \, \text{yr}^{-1}} = A \times 10^{-10} \frac{L_{\text{FIR}}}{L_\odot},$$

where the constant $A$ is of order unity and depends on the details of the initial mass function. The most important uncertainty in this calculation stems from the assumption that the far-IR luminosity is totally powered by star formation, which, given the presence of powerful AGNs in high-z radio galaxies, is a very dubious step. Furthermore, in order to estimate $L_{\text{FIR}}$ from flux densities determined on the Rayleigh-Jeans side of the SED, knowledge of the SED is required. In the absence of observations at shorter (i.e., far-IR) wavelengths, an intrinsic SED must be assumed, adding considerably to the uncertainty in the derived star formation rate.

- The molecular gas mass $M_{\rm H_2}$ is normally derived from emission in CO rotational lines, assuming a conversion factor that is essentially an empirical conversion based on observations of Galactic giant molecular clouds. An extensive literature exists on the general validity of this conversion factor in other galaxies. The conversion factor can be written either in terms of $\text{H}_2$ mass $M_{\text{H}_2}$ through

$$\frac{M_{\text{H}_2}}{M_\odot} = \alpha \frac{L'_{\text{CO}}}{K \text{ km s}^{-1} \text{ pc}^2},$$

where the derivation of $L'_{\text{CO}}$ is discussed in Van der Werf & Israel (1996),
or in terms of H\textsubscript{2} column density through

\[
\frac{N(\text{H}_2)}{\text{cm}^{-2}} = \alpha' \frac{I_{\text{CO}}}{\text{K km s}^{-1}},
\]

where \(I_{\text{CO}}\) is the velocity-integrated CO main beam brightness temperature in K km s\(^{-1}\). The constants in Eqs. (4)–(5) are related through \(\alpha' = 6.25 \times 10^{19} \alpha\), and are proportional to \(\sqrt{n_{\text{H}_2}/T_b}\), where \(n_{\text{H}_2}\) is the H\textsubscript{2} number density and \(T_b\) is the intrinsic brightness temperature of the relevant CO transition (see e.g., Maloney 1990 for a simple derivation of this result). Given the dependence on physical conditions, it is very uncertain whether the standard Galactic conversion factor \(\alpha = 4\) (equivalent to \(\alpha' = 2.5 \times 10^{20}\)) is valid in such extreme objects as dusty high-z radio galaxies. In ULIGs, the molecular gas is both denser and hotter than in the Milky Way. Although these effects tend to cancel each other, the actual value of \(\alpha\) in these objects remains uncertain. Detailed studies by Bryant & Scoville (1996) and Solomon et al. (1997) indicate that in ULIGs, \(\alpha\) may be up to a factor of 4 lower than in Galactic molecular clouds.

- The molecular gas mass can also be estimated from the dust mass assuming a ratio of gas mass to dust mass, defined by \(X = M_g/M_d\). The appropriate value for high-z radio galaxies is difficult to choose \textit{a priori}, given that \(X\) ranges from \(<150\) in the Milky Way (Savage & Mathis 1979), through approximately 500 in nearby spirals (Devereux & Young 1990) and low-z ULIGs (Sanders \textit{et al.} 1991), to much higher values in damped Ly\(\alpha\) systems at \(z > 2\) (Fall \textit{et al.} 1989; Pettini \textit{et al.} 1994). However, in the four high-z QSOs where both CO and dust emission have been detected (H1413+117, IRAS F10241+4724, BR 1202–0725 and BRI 1335–0417), the data point to a value of \(X \sim 500\), again similar to that in local ULIGs. The dust mass \(M_d\) follows from

\[
M_d = \frac{1}{1 + z} \frac{S_\nu \, D_L^2}{k_d(\nu_0) \, B_{\nu_0}(T_d)},
\]

where \(S_\nu\) is the thermal flux density observed at frequency \(\nu\), \(k_d(\nu_0)\) is the dust mass absorption coefficient at rest frequency \(\nu_0 = \nu(1 + z)\), \(T_d\) is the temperature of the dust grains, \(B_\nu(T)\) is the Planck function at frequency \(\nu\) and temperature \(T\), and \(D_L\) is the luminosity distance. In the Rayleigh-Jeans regime, \(T_d\) enters in Eq. (6) in the first power, and given that its plausible range is from 30 to 70 K, it produces some uncertainty
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Table 1. Submillimetre observations of dust emission in high-z radio galaxies. Upper limits represent 3σ values and are only included for observations carried out with bolometer array instruments. In order to derive far-IR luminosities, an Arp 220-like SED has been assumed. Dust masses are calculated for a dust temperature of 50 K, appropriate for the adopted SED.

| Name               | z    | $S_{0.85\,\mu m}$ [mJy] | $L_{\text{FIR}}$ [L$_\odot$] | $M_{\text{dust}}$ [M$_\odot$] | notes |
|--------------------|------|--------------------------|-------------------------------|-------------------------------|-------|
| 6C 0140+326        | 4.41 | < 4.5                    | < 6.8 · 10$^{12}$             | < 1.5 · 10$^{8}$             | 1     |
| 8C 1435+635        | 4.25 | 8.3                      | 1.2 · 10$^{13}$               | 2.8 · 10$^{8}$               | 2     |
| 4C 41.17           | 3.80 | 12.3                     | 1.7 · 10$^{13}$               | 4.3 · 10$^{8}$               | 3     |
| 4C 60.07           | 3.79 | 11.0                     | 1.5 · 10$^{13}$               | 3.8 · 10$^{8}$               | 1     |
| 6C 0932+412        | 3.67 | < 4.8                    | < 6.6 · 10$^{12}$             | < 1.7 · 10$^{8}$             | 3     |
| 6C 1909+722        | 3.54 | 12.4                     | 1.5 · 10$^{13}$               | 4.4 · 10$^{8}$               | 1     |
| 6C 1232+39         | 3.22 | 3.9                      | 5.0 · 10$^{12}$               | 1.4 · 10$^{8}$               | 3     |
| MG 1019+0535       | 2.76 | 14.7                     | 1.8 · 10$^{13}$               | 5.7 · 10$^{8}$               | 4     |
| 3C 257             | 2.47 | 3.9                      | 4.5 · 10$^{12}$               | 1.6 · 10$^{8}$               | 3     |
| 53W 002            | 2.39 | < 3.3                    | < 3.7 · 10$^{12}$             | < 1.3 · 10$^{8}$             | 3     |
| 6C 0930+38         | 2.39 | < 3.6                    | < 4.0 · 10$^{12}$             | < 1.4 · 10$^{8}$             | 3     |
| 6C 0901+35         | 1.91 | < 3.6                    | < 3.7 · 10$^{12}$             | < 1.5 · 10$^{8}$             | 3     |
| 6C 0905+39         | 1.88 | 2.8                      | 2.8 · 10$^{12}$               | 1.2 · 10$^{8}$               | 3     |
| 6C 1204+37         | 1.78 | < 3.0                    | < 2.9 · 10$^{12}$             | < 1.3 · 10$^{8}$             | 3     |
| 3C 294             | 1.78 | < 2.4                    | < 2.3 · 10$^{12}$             | < 1.0 · 10$^{8}$             | 3     |
| 3C 241             | 1.62 | < 4.5                    | < 4.2 · 10$^{12}$             | < 2.0 · 10$^{8}$             | 3     |
| 3C 324             | 1.21 | < 3.1                    | < 2.4 · 10$^{12}$             | < 1.4 · 10$^{8}$             | 3     |
| 3C 217             | 0.89 | < 2.4                    | < 1.5 · 10$^{12}$             | < 9.9 · 10$^{7}$             | 3     |
| 3C 265             | 0.81 | < 3.0                    | < 1.7 · 10$^{12}$             | < 1.2 · 10$^{8}$             | 3     |
| 3C 340             | 0.78 | < 3.6                    | < 2.0 · 10$^{12}$             | < 1.4 · 10$^{8}$             | 3     |
| 3C 277.2           | 0.76 | < 3.3                    | < 1.8 · 10$^{12}$             | < 1.3 · 10$^{8}$             | 3     |

1 unpublished SCUBA data  2 Ivison et al. (1998)  3 Hughes & Dunlop (1998)  4 Cimatti et al. (1998)  5 Best et al. (1998b)

in the derived dust mass, that can only be reduced by observing a well-sampled SED, including the temperature-sensitive Wien side. However, $k_d$ is a more serious source of uncertainty. Estimates of $k_d$ at 800 µm in the Milky Way cover almost two orders of magnitude (e.g., Draine & Lee 1984 versus Rowan-Robinson 1986). As a reasonable compromise, a value $k_d = 1\, \text{cm}^2\, \text{g}^{-1}$ at 800 µm is adopted here, and $k_d \propto \nu^2$ for $\lambda > 100\, \mu m$, which leaves about a factor of 2.5 uncertainty in both directions. Finally, a more subtle uncertainty arises from the implicit assumption of isothermal dust emission, the dangers of which are demonstrated by Draine (1990) in an instructive example.

Table 1 summarizes the current observational situation in submillimetre studies of radio galaxies at cosmologically significant redshifts. Given the uncertainties described above it is advisable to minimize the number of uncertain
steps in the analysis. Hence we concentrate on the derived far-IR luminosities and dust masses, and avoid the additional uncertainties resulting from converting these values into star formation rates and molecular gas masses.

Inspection of Table 1 shows that the success rate for the detection of thermal submillimetre emission from radio galaxies is highest for high-\(z\) objects: for \(z > 2.4\), the detection rate is 77%, while for \(z < 2.4\) the detection rate is only 8%. It is tempting to interpret this result as an evolution effect in the radio galaxy population. In this case it would be concluded that large far-IR luminosities and dust masses in radio galaxies are much more common at high redshift than at low redshift. Interpreting the far-IR luminosities as reflecting immense star formation rates in extremely gas-rich galaxies (as concluded from the large dust masses), these results provide strong support for the “initial starburst” scenario. Indeed, derived star formation rates are in the range suggested by Eq. (1). Taking 4C 41.17 as an example, the inferred star formation rate would be \(\sim 1700 M_{\odot} \text{yr}^{-1}\). This value is significantly higher than the value \(\dot{M}_* \sim 60 - 440 M_{\odot} \text{yr}^{-1}\) derived by Dey et al. (1997) from spectroscopy of the young stellar population in the rest-frame ultraviolet, but given the large dust mass in 4C 41.17, significant extinction is expected, naturally accounting for the discrepancy. Assuming a gas/dust mass ratio of 500, the far-IR derived star formation rate would turn the entire gas reservoir into stars in a burst lasting about \(10^8\) yr, which is a typical time scale for a starburst.

However, there is a subtle selection effect that may be responsible for the high success rate of the detection of thermal submillimetre emission for \(z > 2.4\). The highest redshift objects in Table 1 also have the highest radio powers. Given the good correlation between radio power and far-IR luminosity in low-\(z\) radio galaxies (e.g., Heckman et al. 1994; Hes et al. 1995), it is to be expected that the highest redshift radio galaxies in Table 1 also have the highest far-IR luminosities. But since (as shown in Fig. 1) the observed submillimetre flux density does not drop very much with redshift for a given far-IR luminosity, this situation will naturally lead to a higher submillimetre detection rate for the higher redshift galaxies, simply because the way they are selected makes them intrinsically more luminous. The high submillimetre detection rate for \(z > 2.4\) radio galaxies may result entirely from this effect. Perhaps significantly, one of the two high-\(z\) radio galaxies not detected in the submillimetre, 6C0140+326 at \(z = 4.41\), has a much lower radio power than the other high-\(z\) radio galaxies in Table 1 (Rawlings et al. 1995). Thus, before a conclusion can be reached on the role of dust and far-IR emission in the evolution of the radio galaxy population, this selection effect must be addressed. Submillimetre observations of intrinsically fainter high-\(z\) radio sources will be able to quantify the role of
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Figure 2. Comparison of far-IR and CO luminosities of low-z and high-z radio galaxies. The region occupied by local starburst galaxies and ULIGs (from Sanders & Mirabel 1996) is indicated. Unlabeled point represent detections of compact and FR class I low-z radio galaxies from Mazzarella et al. (1993).

radio power in the trends signalled above. Intrinsically fainter samples of high-z radio galaxies are now becoming available (e.g., Eales et al. 1997), and SCUBA observations of these sources will be able to supply the required information. This is an extremely urgent, and entirely feasible experiment.

4 Radio galaxies as luminous infrared galaxies

The dangers of blindly using the conversion factors given in Sect. 3 for calculating molecular gas masses are illustrated by considering molecular gas mass estimates for 4C 41.17. Using a gas/dust ratio of 500, an H$_2$ mass $M_{H_2} \sim 2 \times 10^{11} \, M_\odot$ is derived. Using Eq. (4), the corresponding CO signal in the low-J lines is predicted to be $L'_{CO} \sim 5 \times 10^{10} \, K \, km \, s^{-1} \, pc^2$. However, the observed 3σ upper limit is $3 \times 10^{10} \, K \, km \, s^{-1} \, pc^2$ (Evans et al. 1996). Allowing $\alpha$ to become smaller than 4 in Eq. (4) makes the discrepancy larger. Evidently, at least one of the conversion steps used in this analysis is in error.

This example shows the importance of minimizing the number of uncertain steps, and the need to analyse the results in terms of direct observables. For a proper analysis of the CO upper limits and submillimetre detections in radio galaxies, it is most useful to plot $L_{FIR}/L'_{CO}$ as a function of $L_{FIR}$, as in Fig. 2.
This diagram includes some data on low-z radio galaxies and radio-loud QSOs detected in the far-IR and in CO, summarized in Table 2. Figure 2 shows that the ratio $L_{\text{FIR}}/L'_{\text{CO}}$ in local star forming galaxies is strongly luminosity dependent. Low-z radio galaxies cover a similar range of values, but there are significant exceptions, such as Cygnus A. Figure 2 allows an assessment of the significance of the CO non-detections in the dusty high-z radio galaxies 4C 41.17 (Evans et al. 1996) and 8C 1435+635 (Ivison et al. 1998). It is evident that these upper limits still allow parameters consistent with local ULIGs, and are not significant, given the luminosity dependence of the ratio $L_{\text{FIR}}/L'_{\text{CO}}$. However, current millimetre wave interferometers are capable of significantly deeper measurements, and should be able to detect CO emission from the most luminous dusty high-z radio galaxies in the coming years.

For systems where the far-IR luminosity is mostly powered by star formation, Fig. 2 shows that the star formation efficiency (i.e., star formation rate per unit molecular gas mass, as measured by the ratio $L_{\text{FIR}}/L'_{\text{CO}}$) increases with star formation rate (as measured by $L_{\text{FIR}}$). Thus, if the far-IR luminosity of dusty high-z radio galaxies is powered by star formation, star formation in these objects proceeds extremely efficiently, reinforcing the view of an “initial starburst” rapidly converting most of the available gas mass into stars, as in monolithic collapse. It is therefore extremely urgent to obtain CO detections of these high-z radio galaxies, so that their location in Fig. 2 can be determined. Subsequently the question whether star formation dominates the far-IR luminosity must be addressed. A crucial parameter here is the spatial extent of the submillimetre emission. Extended emission would indicate a distributed source of heating, strongly supporting the view that star formation is responsible for the observed far-IR luminosity. A future large (sub)millimetre array will be able to address this question observationally.

### Table 2. Parameters of low-redshift radio galaxies and radio-loud QSOs detected in the far-infrared and (except Cygnus A) in CO emission. $H_2$ masses have been derived according to Eq. (4). Upper limits are 3σ values.

| Name     | $z$  | $L_{\text{FIR}}$ [$L_\odot$] | $L'_{\text{CO}}$ [K km s$^{-1}$ pc$^2$] | $M_{H_2}$ [M$_\odot$] | notes |
|----------|------|-------------------------------|----------------------------------------|------------------------|-------|
| 3C 48    | 0.369| $5.0 \cdot 10^{12}$           | $3.1 \cdot 10^{9}$                    | $1.2 \cdot 10^{10}$    | 1     |
| 4C 12.50 | 0.122| $1.6 \cdot 10^{12}$           | $1.3 \cdot 10^{10}$                    | $5.2 \cdot 10^{10}$    | 2     |
| Cygnus A | 0.057| $5.1 \cdot 10^{11}$           | $< 7.2 \cdot 10^{8}$                  | $< 2.9 \cdot 10^{9}$    | 3     |
| 3C 84    | 0.018| $2.2 \cdot 10^{11}$           | $7.6 \cdot 10^{9}$                    | $3.0 \cdot 10^{10}$    | 4     |
| Centaurus A | 0.002| $6.8 \cdot 10^{9}$           | $7.2 \cdot 10^{7}$                    | $2.9 \cdot 10^{8}$     | 5     |

1 Wink et al. (1997) 2 Mirabel et al. (1989) 3 Mazzarella et al. (1993) 4 Inoue et al. (1996) 5 Eckart et al. (1990)
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