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IRAS 14348–1447, an Ultraluminous Pair of Colliding, Gas-Rich Galaxies: The Birth of a Quasar?

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Ground-based observations of the object IRAS 14348–1447, which was discovered with the Infrared Astronomical Satellite, show that it is an extremely luminous colliding galaxy system that emits more than 95 percent of its energy at far-infrared wavelengths. IRAS 14348–1447, which is receeding from the sun at 8 percent of the speed of light, has a bolometric luminosity more than 100 times larger than that of our galaxy, and is therefore as luminous as optical quasars. New optical, infrared, and spectroscopic measurements suggest that the dominant luminosity source is a dust-enshrouded quasar. The fuel for the intense activity is an enormous supply of molecular gas. Carbon monoxide emission has been detected at a wavelength of 2.6 millimeters by means of a new, more sensitive receiver recently installed on the 12-meter telescope of the National Radio Astronomy Observatory. IRAS 14348–1447 is the most distant and luminous source of carbon monoxide line emission yet detected. The derived mass of interstellar molecular hydrogen is 6×10^{10} solar masses. This value is approximately 20 times that of the molecular gas content of the Milky Way and is similar to the largest masses of atomic hydrogen found in galaxies. A large mass of molecular gas may be a prerequisite for the formation of quasars during strong galactic collisions.

A fundamental discovery of the Infrared Astronomical Satellite [IRAS (*1*)] has been the recognition of a class of luminous galaxies emitting the bulk of their energy at infrared wavelengths (*2*). At bolometric luminosities above 10^{10} $L_\odot$ (equivalent to the total energy emitted by spiral galaxies like the Milky Way; $L_\odot$ is the luminosity of the sun) the space density of infrared galaxies in the "local" universe (*3*) is comparable to, or greater than, that of active and starburst galaxies, and at the highest luminosities ($\geq 10^{12}$ $L_\odot$) the space density of "ultraluminous" infrared galaxies is larger than that of optically selected quasars (*4*). It has been proposed that ultraluminous infrared galaxies are, in fact, dust-enshrouded quasars (*5*). The trigger for this activity is the violent collision or merger of gas-rich spiral galaxies, an event that initially causes a violent starburst (that is, a transient period of rapid star formation), with the subsequent formation of the dust-enshrouded quasar. There has been mounting evidence in recent years that galaxy collisions play an important role in both luminous starbursts and in the formation of some quasars (*6*). However, it is through the subsequent detailed ground-based study of the high-luminosity infrared galaxies detected by IRAS that a more complete picture is emerging of the link between starbursts and quasars. In this report we present data gathered at several wavelengths that give a relatively comprehensive picture of one of the most spectacular ultraluminous infrared objects, IRAS 14348–1447. Of particular importance is the detection of the 2.6-mm line of carbon monoxide, which allows a determination of the total amount of molecular gas in this object.

The observations of IRAS 14348–1447 that are presented here are part of a larger program to study the brightest infrared galaxies detected by IRAS [the IRAS Bright Galaxy Survey (*7*)]. The data collected as part of this survey include optical, near infrared, and radio observations designed to provide as complete a picture as possible of the distribution of emitted radiation over a wide range of the electromagnetic spectrum. In addition, observations of the 21-cm line of atomic hydrogen (H I) and the 2.6-mm line of CO provide a measure of the total neutral gas content, a measurement that is important for assessing the total amount of fuel available for star formation, the formation of exotic nuclear sources such as a massive black hole, or both.

One of the most important initial results of this survey has been the discovery that infrared galaxies seem to show a morphological progression toward more strongly interacting pairs of galaxies as the luminosity of the system increases (*5*). Below 10^{11} $L_\odot$ the vast majority of the infrared objects are isolated galaxies. They appear to be powered by star formation, which is fueled by an abundant supply of molecular gas similar to what occurs in the disks of normal late-type spiral galaxies like the Milky Way. At higher luminosities there is a dramatic increase in the number of interacting systems and the incidence of dominant nonthermal nuclear emission. To date, all of these higher luminosity objects that have been observed in the 2.6-mm CO line show evidence for abundant molecular gas supplies and thus appear to be powered both by luminous starbursts and an active nucleus (*8, 9*). At the highest luminosities ($\geq 10^{12}$ $L_\odot$) the data to date have been less complete, but the preliminary indication was that all of the objects were strongly interacting galaxies powered by a dominant nonthermal source (*5*).

The highest redshift object in the IRAS Bright Galaxy Survey is IRAS 14348–1447 at a distance of approximately 330 megaparsecs (Mpc) (*3*). Figure 1 shows an optical charge-coupled detector (CCD) image of IRAS 14348–1447 obtained with the Palomar 1.5-m telescope (*10*). The isophotal map reveals a double nucleus in addition to an extended disk that is warped on the northeast side. The angular separation between the two nuclei is 4 arc sec, which corresponds to a distance of 10 kpc. The brighter nucleus is to the southwest. The color image in Fig. 2 shows these features more clearly. The total luminosity of the system is equivalent to the bolometric lumi-

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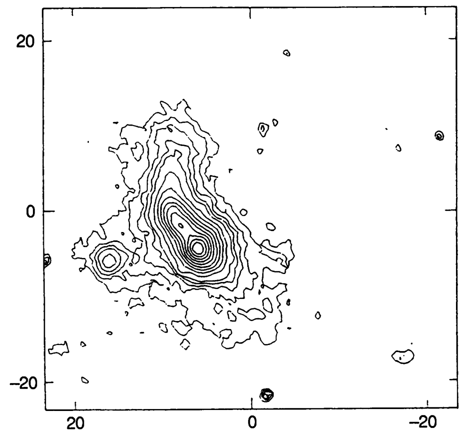

Fig. 1. Isophotal map of direct CCD image (Gunn *r* filter, 0.46 arc sec per pixel) of IRAS 14348–1447. Exposure time was 1200 seconds, and the seeing was ~1.5″. Axes are labeled in arc seconds. Contour levels are 1, 3, 6, 10, 20, . . ., 100% of peak. The total *r*-band magnitude is 15.7. The two nuclei are separated by ~4″ along a northeast-southwest axis. The point source to the east is a foreground star.

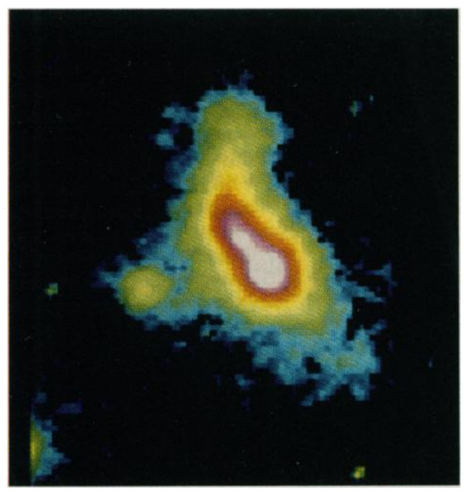

Fig. 2. A false-color optical image of the luminous infrared galaxy IRAS 14348–1447. The original image was obtained through a red filter with a CCD camera on the 1.5-m telescope of the Palomar observatory. Nearly all of the optical emission is from stars located in the disks of the two strongly interacting spiral disk galaxies. White and blue represent optical emission from bright and faint regions, respectively. The nuclei of the two disks are separated by only 4 arc sec, and may, in fact be close to merging. The brighter nucleus presumably already contains a luminous nonthermal source (possibly a dust-enshrouded quasar).

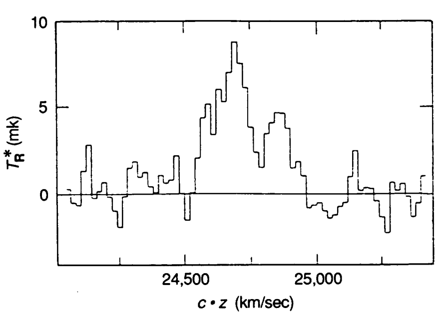

Fig. 3. CO(1→0) emission spectrum of IRAS 14348–1447. This galaxy is receding from the sun at ~8% of the speed of light. The rest frequency of the CO(1→0) emission line at 115.27 GHz (corresponding to a wavelength of 2.6 mm) has been redshifted to the observed frequency of 106.51 GHz, corresponding to a Doppler velocity of 24,732 km sec^{-1}.

nosity of a quasar; however, 90% of the luminosity is emerging in the infrared portion of the spectrum as opposed to the dominant optical and ultraviolet radiation that characterize optically selected quasars.

An optical spectrum of the nuclear emission from IRAS 14348–1447 obtained with the Palomar 5-m telescope shows relatively broad emission lines indicating gas motions up to 2000 km sec^{-1}, and suggesting the presence of a massive, centrally condensed object. The ratio of intensities of the optical emission lines also indicates that the dominant source of ionizing photons is from a nonthermal (power law spectrum) source rather than from hot stars (blackbody spectrum) (*11*). Both of these facts coupled with the extreme total luminosity of the nucleus strongly support the presence of a luminous nonthermal source—a quasar—that is the dominant source of energy output. Further confirmation comes from near-infrared measurements at 1.2, 1.6, and 2.2 μm taken with the Palomar 5-m telescope, which show that the near infrared colors are similar to those observed in quasars.

Observations at CO wavelengths of infrared galaxies are important since they provide a measure of the amount of gas that is available to fuel both star formation and nuclear activity. Owing to both a lack of adequate receiver sensitivity and a lack of complete redshift surveys of infrared bright galaxies, millimeter-wave CO observations of ultraluminous infrared galaxies ($L_{ir} \geq 10^{12}\ L_\odot$) have, until recently, been limited to the nearest such galaxies. However, recent improvements in millimeter-wave receiver technology have now made possible the detection of weak (<10 milliKelvin), broad emission lines, and we have recently detected CO(1→0) emission in several new ultraluminous infrared galaxies (*12*). Figure 3 shows the recent detection of 2.6-mm wavelength emission from the 1→0 rotational transition of the CO molecule in the ultraluminous infrared galaxy IRAS 14348–1447, the most distant object in the IRAS Bright Galaxy Survey.

The CO(1→0) observations were obtained with the National Radio Astronomy Observatory (NRAO) 12-m telescope (*13*) equipped with a dual polarization, superconductor-insulator-superconductor (SIS) receiver with a single sideband receiver noise temperature of ~100 K. A 256-channel filter bank provided a total velocity coverage of 1400 km sec^{-1} at a resolution of 5.4 km sec^{-1}. The spectrometer was adjusted to have a center frequency corresponding to the CO(1→0) transition at the optical redshift measured with the double spectrograph on the 5-m Hale telescope of the Palomar Observatory. Data were obtained by switching the telescope beam on and off the source by means of a secondary reflector nutated at a frequency of 1.25 Hz. This observing mode yielded flat instrumental baselines allowing a more precise determination of the true shape of the CO emission line.

The measured CO line parameters are given in Table 1. The H_2 mass estimate of $6 \times 10^{10} M_\odot$ given in Table 1 was determined from the CO "luminosity" within the telescope beam defined as,

$$L_{CO} = (\pi/4\ d^2_{beam}) \int T^*_R(CO)\ dv \qquad (1)$$

where T^*_R(CO) is the antenna temperature of the 2.6-mm line emission and d_{beam} is the diameter subtended by the antenna beam (55 arc sec full width at half maximum) at the distance of the emitting source. The integral is taken over the entire velocity width of observable CO emission shown in Fig. 3. The mass of molecular gas is computed with the simple expression $M(H_2) = 5.8 \times L_{CO}$, which was determined from extensive studies of molecular clouds in our own galaxy and in nearby starburst galaxies (*14*). A check on the H_2 mass computed from the CO emission is provided by assuming the far-infrared emission is thermal emission from dust. By fitting the 60-μm and 100-μm data to a single temperature dust model with dust emissivity $\epsilon \propto \lambda^{-1}$, where λ

Table 1. IRAS 14348−1447 properties.

Right ascension (1950)	$14^h34^m52^s.3$
Declination (1950)	$-14°47'24''$
Mean velocity $\langle V(CO) \rangle$	24,732 km sec^{-1}
Distance	332 Mpc
Optical diameter (D_{25})	40 kpc
Blue magnitude (B_T)	16.4 mag
Nuclei separation	4″ (10 kpc)
$M(H_2)$	$6 \times 10^{10}\ M_\odot$
L_{fir} (40 to 1000 μm)	$1.6 \times 10^{12}\ L_\odot$
T_{dust}	45 K
M_{dust}	$1.5 \times 10^8\ M_\odot$
Infrared color [J-H]	0.91 mag
Infrared color [H-K]	0.85 mag
Spectral type	Type 2 Seyfert

is the wavelength, we find that the total gas mass, assuming a gas-to-dust ratio of 150, is $2.3 \times 10^{10} M_\odot$, in reasonable agreement with the CO estimate. The H_2 mass of $6 \times 10^{10} M_\odot$ is equivalent to the largest masses of atomic gas (H I) ever observed in spiral galaxies (*15*), suggesting that IRAS 14348–1447 has both an exceptional total amount of gas plus a large fraction of this gas in molecular form.

The detection of IRAS 14348–1447 in the CO(1→0) emission line represents a breakthrough in extragalactic CO observations in that it demonstrates the feasibility of detecting gas-rich galaxies out to redshifts >0.1 with modest aperture telescopes equipped with state-of-the-art millimeter wave receivers. The sensitivity of the NRAO 12-m SIS receiver system is sufficient to have detected IRAS 14348–1447 at twice the distance (that is, a redshift $z \geqslant 0.15$) in less than 4 hours integration time. A larger number of ultraluminous galaxies that have been discovered by IRAS are available for study at these redshifts. It should also be possible to conduct meaningful searches for CO emission in optical and infrared-bright quasars [IRAS 13349+2438 for example (*16*)] to test the hypothesis that all of these objects are part of the evolution of mergers of two gas-rich spirals (*17*).

The extraordinary abundance of neutral gas in IRAS 14348–1447 and in other, less-distant, ultraluminous galaxies, as indicated by observation of CO(1→0) emission (*8, 9*), now strongly suggests that molecular clouds play a fundamental role in the evolution of extreme luminosity galaxies—both violent starbursts and quasars. A plausible scenario for fueling both a burst of star formation and an active nucleus during a galactic collision can be described in the context of cloud-cloud collisions between molecular clouds in the disks of two gas-rich spirals. Unlike the stars in the two galactic systems that rarely, if ever, collide, molecular clouds will suffer frequent collisions. Studies of the molecular cloud population in the disk of our own galaxy and in nearby spiral galaxies (*8, 9*) suggest that molecular clouds will collide frequently during the time that it takes for two spiral disks to interpenetrate, owing to the relatively large cloud cross sections and the small mean-free-path. A high concentration of molecular clouds near the galactic nucleus could then result from dissipation of cloud orbital angular momentum in cloud-cloud collisions, and indeed massive concentrations of molecular gas in the centers of luminous interacting galaxies have recently been detected (*9, 18*). The large increase in gas volume density and the increased cloud collision rate will trigger a nuclear starburst (*19*). Eventually the gas or newly formed stars will build a massive black hole, or add to the mass of a preexisting black hole (*20*). At the stage of ultraluminous infrared galaxies, where the total luminosity equals that of optical quasars, it is presumed that the quasar has already become the dominant energy source, and the starburst luminosity is less important. Eventually the combined pressure of stellar winds from the massive stars, supernovae explosions, and radiation pressure from the quasar will disperse enough of the gas so that the central nonthermal source is relatively unobscured. Such housecleaning may already have begun in the ultraluminous infrared galaxies since it is already possible to see evidence of the broad-line optical spectrum of the central nonthermal source. It thus seems reasonable to assume that these galaxies will in time resemble optically selected quasars characterized by a dominant optical point source.

We believe that IRAS 14348–1447 and other ultraluminous infrared galaxies show a natural link between starburst galaxies and quasars. In the local universe there are sufficient numbers of infrared galaxies to account for the majority of, if not all, quasars. It should be possible in the next few years to study a much larger sample of the more distant, fainter ultraluminous infrared galaxies detected by IRAS, and it will be possible to determine if the numbers of these objects increase at the same rate with increasing redshift as might be expected if the two classes of objects are intimately related. Such observations, in combination with the greatly enhanced angular resolution of images of distant optical quasars that will become available with the launch of the Hubble Space Telescope, should verify that quasars do indeed owe their origin to violent galaxy collisions.

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