Megamasers

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1. INTRODUCTION

In space, equilibrium conditions are extremely rare. As a system is taken further and further from equilibrium, a phenomenon responsible for its relaxation to an equilibrium state becomes progressively more obvious. Nonequilibrium conditions can be sustained for a fairly long time if there is some external perturbation source. Among such objects are galactic and extragalactic masers operating on OH, H_2O, SiO, H_2CO, etc., molecules.

Megamasers are a vivid new phenomenon in space physics. The isotropic luminosity of a molecular OH maser ($\lambda \approx 18$ cm) in the main radio lines of the rotational ground state $J = 3/2\,{}^2\Pi_{3/2}$, observed from the peculiar galaxy IC 4553 (Arp 220),[1] is 10^7 times the luminosity of the "standard" galactic source W 3 (OH), whose luminosity is $L \sim 10^{-5} L_\odot$ ($L_\odot = 4 \cdot 10^{33}$ erg/s is the luminosity of the sun). Hence the name "megamaser." Several new OH megamasers have recently been observed from the galaxies NGC 3690, Mrk 231, and Mrk 273, and from certain IRAS[1)] sources[2] at distances of 2–300 Mpc. Back in the 1970s, OH maser radio emission was observed[3] in the main radio lines of the ground state (1667 and 1665 MHz) from the galaxies M82 and NGC 253. At the time they were called "supermasers," since their isotropic luminosity was one or two orders of magnitude greater than the luminosity of galactic masers. The isotropic luminosity of megamasers, on the other hand, is $L \sim (10\text{–}10^3) L_\odot$ at a redshift $z \sim 0.01$–0.03 for these galaxies.[4] The observed fluxes in the main OH radio lines are several tens of millijanskys [1 jansky (Jy) $= 10^{-23}$ erg/(cm$^2\cdot$s$\cdot$Hz)], and the velocity interval spanned in the line is from 300 to 500 km/s (in the Seyfert galaxies Mrk 231 and Mrk 273 the corresponding figures are $\Delta v \sim 760$ and 1060 km/s, respectively[2b]). A distinctive feature of OH megamasers is that their emission is a broad-band emission at a low gain ($\tau_{1667} < 1$, where τ is the optical thickness).

The first extragalactic maser emission of H_2O molecules in the radio line $6_{16} \to 5_{23}$ ($\lambda \approx 1.35$ cm) to be observed was that from the galaxy M33 (Ref. 5). The most intense water-vapor masers which have been observed are from the galaxies NGC 3079, NGC 4258, and NGC 1068 (Ref. 6), with isotropic luminosities $L \sim (10^2\text{–}10^3) L_\odot$. The typical luminosity of galactic water-vapor sources is $L \sim 10^4 L_\odot$ (an exceptional case is the source W 49, whose isotropic luminosity is $\sim 1 L_\odot$), so the extragalactic H_2O masers—which are sometimes called even "ultramasers"—are also an extremely interesting phenomenon. An emission in the radio line $1_{10} \to 1_{11}$ of H_2CO molecules ($\lambda \approx 6.2$ cm) was recently observed[7] from the galaxy IC 4553, with a luminosity seven orders of magnitude greater than the luminosities of the two known galactic H_2CO masers.

We will be discussing models of extragalactic megamasers below, but we will begin by taking a look at the basic characteristics of the galactic masers. We will be discussing only the OH-molecule megamasers in detail, since they are the phenomenon which has been studied most thoroughly, but we will also take a brief look at H_2O and H_2CO megamasers.

2. MASERS IN THE LOCAL GALAXY

The intense maser radiation in the radio lines of molecules in the local galaxy is characterized by narrow lines ($\Delta\nu \sim 1$–50 kHz) and high brightness temperatures ($T_b \sim 10^{10}$–10^{16} K). In the laboratory, one would use a system of mirrors to arrange repeated passage of the signal in order to achieve a large amplification. Furthermore, extremely high-quality apparatus is required in order to achieve a narrow band in the laboratory. These "complications" do not afflict cosmic masers, in which a large amplification (by a factor up to 10^{13}) is achieved thanks to the long distances involved ($\sim 10^{13}$–10^{16} cm). Under astrophysical conditions there is no phase coherence, since there are no high-quality systems; astronomical masers are thus broadband masers in principle, although in unsaturated operation the bandwidth of the signal being amplified may be narrowed by a factor of $(\tau/\ln 2)^{1/2}$. In the absence of phase coherence of the maser radiation under astrophysical condi-

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tions, one can distinguish a coherence length

$$l_{coh} \approx \frac{\Delta v}{\partial v/\partial z}, \quad (1)$$

which is proportional to the observed linewidth and which is inversely proportional to the systematic change in the velocity in the active medium.

The 1965 discovery[8] of radiation in the main radio lines of OH led the discoverers down a blind alley (the radiation of a "mysterium"). Identification was delayed until the observation of all four of the radio lines[9] belonging to transitions among levels of the hyperfine structure of the rotational ground state of the hydroxyl molecule. It was not until the angular dimensions were measured[10] and found to be very small, however, that it became really clear that a natural cosmic maser was at work here. In the mid-1950s Townes, an American physicist, pointed out that the $6_{16} \to 5_{23}$ transition of the H_2O molecule ($\lambda \sim 1.35$ cm) might be of interest for radio astronomy.[11a] Maser radiation on this transition was indeed observed in the late 1960s (Ref. 11b; back in 1949, Shklovskiĭ[12] had predicted that it would be possible in principle to observe radio lines of OH from clouds in the interstellar medium). Maser radiation was subsequently observed from other molecules, e.g., CH, SiO, CH_3OH, H_2CO, NH_3, and HCN. In addition to having high brightness temperatures, the maser radiation of some objects is highly polarized (circular polarization in OH radio lines and linear polarization in H_2O and SiO radio lines), varies over time, has small angular dimensions, and has a complex spatial structure. Observation with an intercontinental interferometer with a resolution $\sim(300\cdot 10^{-6})''$ revealed[13] that the masers surrounding newly formed stars consist of hundreds of bright condensations 10^{13}–10^{15} cm in size, have different velocities, and have equivalent blackbody temperatures $\sim 10^{14}$ K and higher.

A nonequilibrium emission arises between rotational levels in heavy and light molecules and between hyperfine levels of Λ-doubled rotational levels in light molecules. The lifetimes of maser levels vary from 1 s in heavy molecules to 10^{11} s in light molecules, and the corresponding wavelengths vary from 0.1 to 18 cm. Molecules which contain hydrogen have high probabilities for spontaneous transitions between rotational levels, so they can sustain a nonthermal population of the latter levels at relatively high densities, i.e., at

$$n \leqslant \frac{A}{\sigma v} \sim \frac{10^{-1} - 10^{-3}}{10^{-15}\cdot 10^{5}} \sim 10^{7} - 10^{9}\ \mathrm{cm}^{-3};$$

where A is the spontaneous-transition probability, σ is the cross section for collisional excitation, and v is the thermal velocity.

Intense maser radiation of molecules ($T_b \sim 10^{10}$–10^{16} K) arises in the envelopes of massive young stars and in the envelopes of IR stars (these are mostly giants and supergiants of class M), in which the molecules which emit by a maser mechanism are subject to an intense flux of IR radiation. A weak maser emission of molecules occurs primarily in clouds in the interstellar medium. The reader interested in more details about masers in the local galaxy might look in the reviews by Reid and Moran and by Elitzur.[14]

3. SUMMARY OF THE CHARACTERISTICS OF GALAXIES WITH OH-MOLECULE MEGAMASERS

Galaxies in which megamasers are observed are rich in a molecular gas ($M_{H_2} \sim 4\cdot 10^9$–$2\cdot 10^{10}\, M_\odot$) in comparison with ordinary bright spirals and have a high IR luminosity ($L \sim 10^{11}$–$3\cdot 10^{12}\, L_\odot$). These galaxies are also distinguished by an exceedingly intense burst of star formation (IC 4553, NGC 3690), galactic nuclei exhibiting Seyfert properties (Mrk 231, Mrk 273), and intense fluxes in the UV range. The ratio of the IR luminosity to the UV luminosity is ~ 10–80 for some of the galaxies which have been observed.[4] The morphology of IRAS galaxies of high luminosity indicates, as was pointed out in Ref. 15, that many of these galaxies are coalesced or close contact pairs; this circumstance seems to initiate bursts of star formation. For example, NGC 3690 and IC 4553 are interacting galaxies with a well-developed sprial structure (galaxies of type Sc). Some of the observed galaxies (III ZW 35, II ZW 96) are compact Zwicky galaxies, which are similar in physical nature to Markaryan galaxies,[17] as was pointed out in Ref. 16. In general, all galaxies with megamasers are structurally peculiar, and the intense star formation in them is not by itself a sufficient condition for maser emission.[18] All these galaxies have an active nucleus. It follows from observations taken with the VLA instrument[19] that peculiar interacting spirals, like compact galaxies, have a relatively high continuum radio flux. Furthermore, as was mentioned in Ref. 20, a high correlation is observed between the ratio and far-IR fluxes in many IRAS galaxies. The optical emission of some of these galaxies (IC 4553) reveals dust bands and a disk-shaped structure. An absorbing structure of atomic hydrogen has been found over a wide radial-velocity interval in galaxies having megamasers[2,4]; the width of this interval in the galaxy Mrk 273, for example, is ~ 430 km/s. As we have already mentioned, the distance to the megamaser galaxies ranges up to 300 Mpc (this limit is imposed on the distance by the capabilities of the IRAS satellite), if Hubble's constant is $H_0 \sim 75$ km/(s·Mpc).

The most interesting properties of these galaxies, however, are their IR characteristics. In the first place, galaxies having a maser emission reveal a pronounced excess in the IR emission at 25 and 60 μm, which is not found in other IRAS galaxies[18] (see, for example, the IRAS review of active galaxies and the study of the IRAS phenomenon in Refs. 21 and 22). Furthermore, these galaxies have an exceedingly steep spectrum in the mid-IR region ($F_{25\,\mu m}/F_{12\,\mu m} > 4.2$) and an unusually gently sloping spectrum in the far-IR region ($F_{100\,\mu m}/F_{60\,\mu m} \lesssim 1.4$). These features, combined with the active nucleus and the extended regions of star formation, distinguish these galaxies from normal spirals. In galaxies with megamasers, the stars form either around the nucleus or in the galactic disk,[23] over a length scale of 100–750 pc. Of the ten brightest IRAS galaxies with luminosities $L > 10^{12} L_\odot$, five are OH megamasers.[2,24] The luminosity of IRAS galaxies, $10^{12} L_\odot$, is comparable to the luminosity of a quasar, suggesting an evolutionary relationship between these objects. We might note that if bursts of star formation were far more intense in the early epochs, one could not rule out the possibility that megamasers or even gigamasers might be observable from galaxies with a large redshift.[2)]

In the local galaxy, a weak analog of the maser emission of extragalactic OH molecules could probably be the anomalous emission of these molecules in the main radio lines from dust clouds,[25] in which the kinetic temperature is ~ 10 K.

4. PRODUCTION OF OH MOLECULES, THEIR ABUNDANCE, AND SPECTROSCOPIC FEATURES OF THE LOW-LYING ROTATIONAL LEVELS

The reactions in which molecules are produced, participate, and are destroyed under astrophysical conditions are quite different from the conditions which can be arranged in the laboratory. The primary distinguishing features are the low temperatures and densities. In clouds of interstellar medium in the local galaxy, there are differences not only in the temperature and density ($T \sim 10$–100 K, $n \sim 10$–10^4 cm^{-3}) but also in the radiation fields. While the effects of radiation fields are significant in diffuse clouds, they can be ignored in dense clouds. In dense clouds with $n \sim 10^3$ cm^{-3}, cosmic rays become important, initiating ion-molecule reactions. In dust clouds with $n \sim 10^3$ cm^{-3} the radiation fields are weak but not negligible. The primary gas-phase reactions in which OH molecules are produced and which are characteristic of diffuse clouds are the following:

$$H^+ \xrightarrow{O} O^+ \xrightarrow{H_2} OH^+ \xrightarrow{H_2} H_2O^+ \xrightarrow{H_2} H_3O^+ \begin{cases} \xrightarrow{e^-} H_2O \xrightarrow{h\nu} OH + H, \\ \xrightarrow{e^-} OH + H_2. \end{cases} \qquad (2)$$

Which of the reactions at the end of chain (2) is predominant is not known at this point (in a chemical modeling, their probabilities are taken to be equal). In dense clouds, with a low content of atomic hydrogen, the following reactions are important:

$$\begin{aligned} H_2^+ + H_2 &\to H_3^+ + H, \\ H_3^+ + O &\to OH^+ + H_2. \end{aligned} \qquad (3)$$

The relative abundance of the OH radical ($[n_{OH}]/[n_{H_2}]$) varies with the density, the kinetic temperature, and the concentration of metals in the clouds, from $4\cdot 10^{-6}$ to $2\cdot 10^{-8}$. The relative abundance of OH is also influenced by the ratio $[C]/[O]$, the electron density, the proximity of ionization sources, and the mass and evolutionary status of the cloud, so it is not a trivial matter to derive theoretically the molecular abundance in some cloud, even in the local galaxy. In calculations of molecular abundance, a state of static equilibrium is a good approximation only for diffuse clouds, since their lifetimes are substantially greater than 10^7 yr. In dense clouds, far from collapse, a quasistatic situation is again possible. During a collapse, a quasistatic situation cannot be reached since the free-fall time $t_{ff} \approx 4\cdot 10^7/n_{H_2}^{1/2}$ yr is short, and a nonstatic approximation is used to calculate molecular abundances in this case.[26a] For further estimates, we adopt a relative abundance $\sim 10^{-6}$ for the OH radical, and we note that the primary mechanism for the production of OH molecules in clouds with densities $n \lesssim 10^3$ cm^{-3} is the photodissociation of H_2O molecules, whose relative abundance is[26b] $\sim 10^{-5}$–10^{-7}.

Figure 1 shows the scheme of low-lying rotational levels of the OH molecule, which take an intermediate position between Hund's cases a and b in terms of the coupling of angular momenta (in case a, the spin-orbit interaction is

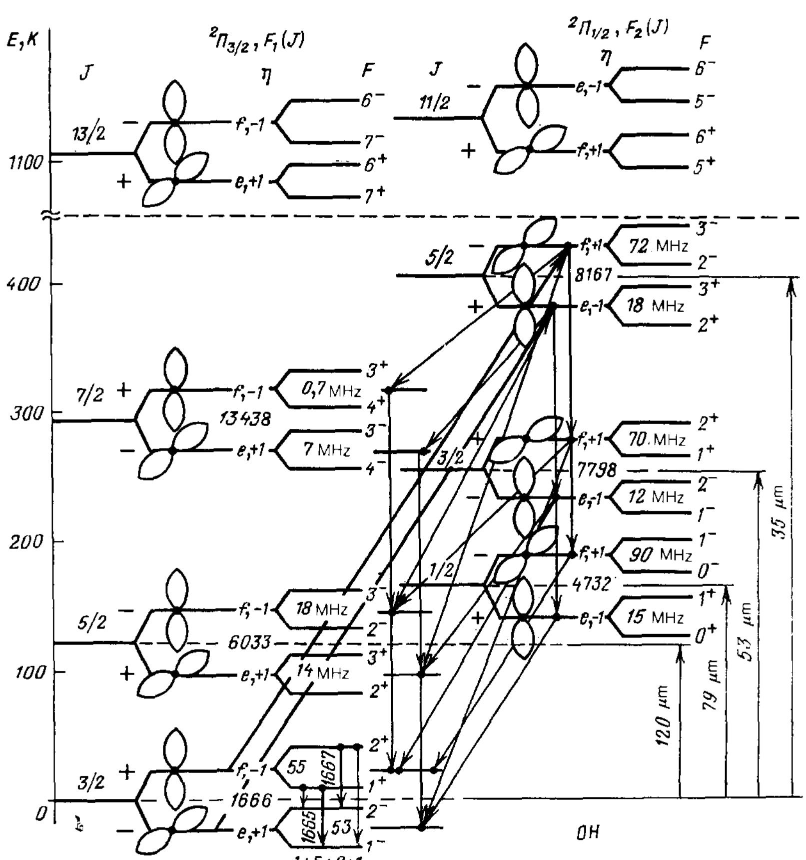

FIG. 1. Structure of the low-lying rotational levels of the OH molecule. The Λ-doubling and the hyperfine splitting are not drawn to scale.

strong, while the spin-rotation interaction is weak; case b is just the opposite). We see from Fig. 1, where J is the total angular momentum without the nuclear spin ($I = 1/2$, $F = J \pm I$), that the rotational levels consist of two bands, $F_1(J)^2\Pi_{3/2}$ and $F_2(J)^2\Pi_{1/2}$ in which the $^2\Pi_{1/2}$ electronic state lies at an energy higher than that of the $^2\Pi_{3/2}$ electronic state (an inverted fine structure). The symmetry of the electron wave functions under reflection in the plane of the axis of the molecule determines the parity of the Λ-doubled rotational levels ($\pm$). According to the established nomenclature,[27] levels with parity $+(-1)^{J-1/2}$ are e levels of Λ-doublets, while those with parity $-(-1)^{J-1/2}$ are f levels of Λ-doublets. Furthermore, the same wave functions are either symmetric or antisymmetric ($\eta = \pm 1$) under reflection in the plane of rotation of the molecule. This symmetry corresponds to a certain predominant orientation $p\pi$ of the electron cloud. An electron cloud for levels F_1e and F_2f is oriented predominantly in the plane of rotation; that for levels F_1f and F_2e is perpendicular to this plane.[28] Taking this symmetry into account, we can write the wave function corresponding to the low-lying rotational levels in the form[29b]

$$\psi = c_J \cos\varphi + d_J \sin\varphi, \tag{4}$$

where c_J and d_J are J-dependent mixing factors, whose squares are the probabilities that an unpaired $p\pi$ electron cloud will be oriented perpendicular or parallel to the rotation plane, and φ is the angle in the x, y plane, which is perpendicular to the z axis (here the z axis is the axis of the molecule and lies in the plane of rotation of the molecule).

5. POSSIBLE MECHANISMS FOR THE FORMATION OF A POPULATION INVERSION IN OH MEGAMASERS; ENERGY ESTIMATES

It follows from an analysis of the observational data that a broad-emission in the main radio lines of OH molecules from extragalactic sources is probably due to a slight maser amplification ($\tau \lesssim 1$) by OH molecules of the radio continuum of the disk and the nucleus. There is the possibility in principle of a model in which megamasers are the sum of the maser radiation from 10^6–10^7 separate young massive stars, in whose envelopes OH masers of type W 3 (OH) are "sitting." That model seems a bit contrived since it would be unlikely to have some 10^7 O stars in a common evolutionary stage in a velocity interval $\sim$300–500 km/s. Furthermore, it follows from observations of the peculiar galaxy IC 4553 that the emission in the main radio lines of OH is extremely extended.

The levels of OH molecules under the conditions prevailing in clouds of the interstellar medium of any galaxy might be inverted by UV or IR radiation. Let us examine this possibility. Clouds in spiral galaxies form ring structures with respect to the nucleus, and in the surface layers of these structures photodissociation reactions could occur intensely. Water molecules irradiated by UV radiation will undergo dissociation. The photodissociation dynamics of H_2O is not simple, although the nature of the photofragments is known for all wavelength regions of the radiation causing the dissociation of the molecule.[30] As was pointed out in Ref. 31, about 80% of the H_2O molecules will undergo dissociation in accordance with the main primary reaction

$$H_2O\,(^1A_1) + h\nu\,(1350-1900\,\text{Å}) \rightarrow H_2O\,(^1B_1) \rightarrow OH\,(X^2\Pi) + H\,(^2S). \tag{5}$$

Photodissociation in the first absorption band occurs along the well-determined[29b] potential surface of the H_2O molecule and is accompanied by the formation of an OH molecule in the electronic state $^2\Pi$. A high degree of inversion of the F_1f levels of Λ-doublets in the $^2\Pi_{3/2}$ band results from the preservation of the spatial orientation of the electron cloud during photodissociation; i.e., during the photodissociation, the orientation of the $1b_1$ orbital of the H_2O molecule remains parallel to the $p\pi$ orbital of OH. This fact has been confirmed experimentally in the photolysis of "cold" water.[29] Could conditions suitable for the photodissociation of H_2O arise in the clouds of the disk of extragalactic sources? How many UV photons would be required to explain the energy scales of OH megamasers? Let us make a few assumptions in the way of a model. It is natural to assume that the properties of the dust in IRAS galaxies (the extinction, the albedo, the size, and the composition) differ only slightly from the properties of the dust in the local galaxy, which are generally not known very well. This is an important point, since the dust absorbs and reradiates UV radiation. The molecular disk in bright sprial galaxies within $\leqslant 1$ kpc of the galactic center seems to consist of clouds which may be similar to the clouds in the local galaxy; the observational data support this possibility, if only indirectly.[32] If a megamaser is to be realized, the photodissociation of the H_2O must occur in one of the following settings: at the nucleus of a diffuse cloud with $n \sim 2500$ cm^{-3} and $T \sim 22$ K (Ref. 33a), in the medium between condensations of a dust cloud with $n \sim 3\cdot 10^3$ cm^{-3} and $T \sim 30$ K (Ref. 33b), or in gigantic molecular clouds.[33c] To derive some qualitative estimates of the extreme case, we assume that the values $n \sim 10^3$ cm^{-3} and $T \sim 25$ K prevail at the photodissociation surface of the molecular disk in a model cloud. The total number of "active" OH molecules in a source with a luminosity $L_{OH} \sim 100 L_\odot$ must be

$$N = \frac{L_{OH}}{h\nu W\,UV} \sim 4\cdot 10^{60}\ \text{molecules}, \tag{6}$$

where $W_{UV} \sim 10^{-8}$ s^{-1} is the probability for the interaction of the H_2O molecule with the UV radiation. In estimating the probability, we took the flux to be three orders of magnitude greater than the average UV flux in the local galaxy.[34] Hence the total mass of the clouds with $[n_{OH}]/[n_{H_2}] \sim 10^{-6}$ is $M_{H_2} \sim 7\cdot 10^{10} M_\odot$, if we assume that the active OH molecules constitute 10% of the total number.

On the other hand, if we ignore the dust and use $L_{OH} \sim 100 L_\odot$, we find the rate of destruction of H_2O molecules to be $(L_{OH}/h\nu)m_{H_2O} \sim 10^{30}$ g/s. Even with $[n_{H_2O}]/[n_{H_2}] \sim 10^{-5}$, the consumption of H_2 molecules in the photodissociation process would be $\dot{M}_{H_2} \sim 10^{35}$ g/s; in this case, the entire mass of interstellar gas would be converted in a time of only $t \sim M_{H_2}/\dot{M}_{H_2} \sim 1.4\cdot 10^9$ s, i.e., 47 yr. Incorporating the dust not only leads to a screening of the molecules but also has the further consequence that, in the case of H_2O, an ice cloud of dust particles could serve as the reservoir required to regenerate the water vapor, although this reservoir would have an extremely brief life.[35] One might get the impression that there is a large margin here in terms of the UV luminosity, since we have $L_{OH} \sim 3\cdot 10^{53}$ photons/s and

$L_{UV} \sim 5\cdot 10^{55}$ photons/s in the case of the source Mrk 231, for example. That impression is illusory, however, since the operation of this mechanism would require "cold" H_2O molecules with $T_{kin} \lesssim 25$ K, and these molecules would necessarily be screened by dust; the flux of UV photons to these molecules would be substantially lower than that according to the estimate $W_{UV} \sim 10^{-8}$ s^{-1}. Although the length of the active region of OH molecules in the photodissociation of H_2O molecules turns out to be acceptable [in the source Mrk 231, for example, we would have $l \sim 1.5\cdot 10^{18}$ cm at an unsaturated gain $\exp(\alpha l) \sim 2$], this mechanism for the formation of an inversion in terms of rotational levels in the OH molecule still could not be the primary mechanism. The probability for an interaction of OH molecules with IR radiation is five or six orders of magnitude higher than the probability for the interaction of H_2O with UV radiation for any reasonable geometry of the megamasers, even when we note that the photodissociation process is of a broad-band nature, $\Delta\lambda \sim 550$ Å (5). Observational confirmation that the photodissociation mechanism for pumping is untenable comes from the observation[36a] in the galaxy IC 4553 of absorption in radio lines of the rotational state $J = 5/2\,^2\Pi_{3/2}$ ($\lambda \approx 5$ cm); this absorption should not occur in the case of this particular excitation mechanism.

The probability for the interaction of OH molecules with IR radiation with $\lambda \approx 35\,\mu$m in the source Mrk 231, for example, at a distance of 10 pc would be $W_{IR} \sim (F_{35\,\mu m}\lambda^2/4\pi 2h\nu)A \sim 0.007$ s^{-1} at $F_{35\,\mu m} \sim 5\cdot 10^{-8}$ erg/cm^2 and $A \sim 0.017$ s^{-1}, so at low densities only IR radiation could determine the level populations of OH, CH, H_2CO, H_2O, etc., molecules. We note in passing that the probability for collisions of molecules with H_2 or with H at $T \sim 25$ K and $n \sim 10^3$ cm^{-3} in clouds is extremely low, i.e., many orders of magnitude lower than the probability for their interaction with IR radiation. Furthermore, absorption is also observed[36b] in radio lines of the state $J = 1/2$ ($\lambda \approx 6$ cm); this absorption should not occur in the case of a collisional excitation of OH with H_2.

We have a few preliminary comments regarding the IR pumping of OH molecules. For amplification to be achieved in the main radio lines, with $\Delta F = 0$, $F' \to F = 2^+ \to 2^-$ (1667 MHz) and $F' \to F = 1^+ \to 1^-$ (1665 MHz), the IR pump or any other pump would have to transport the population from the $F = 1^-, 2^-$ hyperfine levels to the $F = 1^+$, 2^+ hyperfine levels (Fig. 1). For this to happen there must be an effective suppression of competing processes.[37] Competing transitions can be suppressed, for example, as the result of an overlap of certain IR lines at a high kinetic temperature in the cloud, $T_{kin} \gtrsim 500$ K, or as a result of microturbulence motions in the cloud.[38] In other words, some special conditions would have to prevail. For amplification to occur in the radio lines of satellites, with $\Delta F = \pm 1$, $F' \to F = 2^+ \to 1^-$ (1720 MHz) and $F' \to F = 1^+ \to 2^-$ (1612 MHz), which connect sublevels of Λ-doublets with different total angular momenta, there would be no need to suppress competing processes. All that would be needed here is a redistribution of the population in the sublevels of the same parity, i.e., transport of population from the $F = 2^+$ sublevel to the $F = 1^+$ sublevel and from the $F = 2^-$ sublevel to the $F = 1^-$ sublevel, for amplification at the 1612-MHz radio line, or from the $F = 1^+$ sublevel to the $F = 2^+$ sublevel and from the $F = 1^-$ sublevel to the $F = 2^-$ level, for amplification at the 1720-MHz radio line. These conditions can be satisfied easily after IR radiation with $\lambda \approx 120$ μm ($J = 5/2\,^2\Pi_{3/2} \to J = 3/2\,^2\Pi_{3/2}$) and $\lambda \approx 79\,\mu$m ($J = 1/2\,^2\Pi_{1/2} \to J = 3/2\,^2\Pi_{3/2}$) passes through a certain optical thickness. This process was pointed out by Litvak.[39] It thus appears to us that the pumping mechanism in megamasers would have to be a "common" mechanism, because of the broad-band nature of the radiation here. One mechanism which meets this requirement, for example, is the mechanism of a redistribution of population corresponding to transitions with $\Delta F = \pm 1$. On the other hand, we would have to incorporate in this mechanism at least a slight suppression of competing processes, since main radio lines with $\Delta F = 0$ are being amplified. This "common" process might be, for example, the asymmetry which was found in Ref. 40 in the matrix elements of dipole transitions: $J = 5/2$, $F', \xi', {}^2\Pi_{1/2} \to J = 3/2, F, \xi, {}^2\Pi_{3/2}$ ($\lambda \approx 35\,\mu$) and $J = 3/2$, $F', \xi', {}^2\Pi_{1/2} \to J = 3/2, F, \xi, {}^2\Pi_{3/2}$ ($\lambda \approx 53\,\mu$m). More precisely, we are talking about an asymmetry in the competing transitions (for the transition $J', F', \xi' \to J, F, \xi$, a competing transition is $J', F', -\xi' \to J, F, -\xi$). This asymmetry is not simply a small admixture in the transition probability because of a cubic dependence of the Einstein coefficient $A_{J'F'\xi' \to J,F,\xi}$ on the frequency (the frequencies of IR mirror transitions are different, because of a difference in Λ and in the hyperfine splitting of the rotational levels $J = 5/2\,^2\Pi_{1/2}$ and $J = 3/2\,^2\Pi_{3/2}$; see also Fig. 1); it is due to an effect of the electronic state $^2\Sigma^-$ (see the discussion in Ref. 37a). The transitions with $\lambda \approx 35\,\mu$m have an inverting tendency for the ground-state levels, and those with $\lambda \approx 53\,\mu$m have an anti-inverting tendency, as was pointed out in Ref. 37a. The degree of inversion depends on the relative intensity of the IR radiation at $\lambda \approx 53\,\mu$m, i.e., on the steepness of the spectrum. Bujarrabel *et al.*[37a] found that the degree of inversion in their calculations did not exceed a few percent, i.e., did not exceed the degree of asymmetry of the Einstein coefficients:

$$\frac{|\mu_{-J',J}|^2}{|\mu_{J',-J}|^2}\left(\frac{\nu_{-J',J}}{\nu_{J',-J}}\right)^3 \sim 3\cdot 10^{-2} \tag{7}$$

accordingly, during the actual absorption of the photons at $\lambda \approx 35\,\mu$m, which break up into lower-frequency photons in cascade transitions among levels of the $^2\Pi_{1/2}$ band to the ground state (Fig. 1), a slight inversion of the Λ-doublet $J = 3/2\,^2\Pi_{3/2}$ of the OH molecule will always arise [the survival probability (φ) of the photons with $\lambda \approx 35\,\mu$m is exceedingly low: $\varphi \sim 0.05$–0.005]. For an estimate we assume $\Delta n/n_{OH} \sim 1\%$ and $n \sim 10^3$ cm^{-3}, i.e., $\Delta n \sim 10^{-5}$ cm^{-3} with $[n_{OH}]/[n_{H_2}] \sim 10^{-6}$. Good amplification in the radio line at 1667 MHz, i.e., $\exp(\alpha l) \sim 2$ in the unsaturated regime, would thus require

$$\alpha = \frac{\lambda^2 \Delta n\,(2F'+1)\,A_{F'\to F}}{8\pi\Delta\nu} \sim 3\cdot 10^{-20}\ \text{cm}^{-1}, \tag{8}$$

where $A_{F'\to F}$ is the probability for the spontaneous transition $2^+ \to 2^- = 7.8\cdot 10^{-11}$ s^{-1}, and $\Delta\nu$ is the width of the maser radio line, $\sim 1.6\cdot 10^6$ Hz ≈ 300 km/s. The value $(\alpha l) \sim 0.7$ is reached over a distance of 8 pc. The slope observed in the spectrum in the mid-IR region from certain spiral galaxies is opposite that which would be required (our preliminary calculation with new IR frequencies[41] has shown that the appearance of a level inversion in the ground state would require that the ratio $F_{53\,\mu m}/F_{35\,\mu m}$ be $\leqslant 0.2$). According to the

IRAS data,[18] in the galaxies Mrk 231, Mrk 273, Arp 220, and IRAS 1708-0014 that ratio is $F_{25\mu m}/F_{12\mu m} \geqslant 4.2$; in other words, these inequalities are incompatible, although they were found at different wavelengths (but not greatly different). A point worth noting here is that the model IR spectrum of IRAS galaxies[42] consists of a disk component, a "starburst" component, and a Seyfert component. In turn, the disk component of the IR spectrum consists of at least two components: a warm component, associated with OB stars and young star-forming complexes, and a cold component, associated with a diffuse neutral interstellar medium. Since the observed spectrum in the IRAS sources is integrated over the entire galaxy, at this point it is essentially impossible to distinguish reliably the components of the IR spectrum (a better spatial resolution is required).

To conclude this section of the paper, we would like to mention yet another mechanism, which was proposed in Ref. 37b and which also involves the possibility of formation of a slight inversion between upper sublevels of the ground state, if the OH molecules are under conditions such that the dust is fairly hot. The far-IR radiation of an optically thin dust is characterized by the distribution[37b]

$$F(\nu) = \tau_d(\nu)\,(e^{h\nu/KT_d} - 1)^{-1}, \qquad (9)$$

where $\tau_d(\nu)$ is the optical thickness of the dust, given by $\tau_d(\nu) = \tau_d(\nu_0)(\nu/\nu_0)^p$; T_d is the temperature of the dust; the exponent p lies in the interval $1.5 \leqslant p \leqslant 3.5$ and depends on the particular type of dust particles; and $\lambda_0 \approx 80\ \mu m$. Since the Λ splitting increases with increasing J (Fig. 1), IR transitions from upper sublevels of the ground state have a frequency higher than that of IR transitions from lower sublevels. As was shown in Ref. 37b, the value of $F(\nu + \delta)$, where δ is the difference between the frequencies of the competing transitions ($\delta/\nu \sim 10^{-3}$), will be higher than the value of $F(\nu)$, so at a certain T_d there will be an inversion of the upper sublevels with respect to the lower ones. In this mechanism, the inversion of the sublevels of the $J = 3/2$ ground state is influenced primarily by the most probable transition, $J = 5/2\ {}^2\Pi_{3/2} \to J = 3/2\ {}^2\Pi_{3/2}$ ($\lambda \approx 120\ \mu m$). The final choice of an IR pumping mechanism has yet to be made.

6. H_2O and H_2CO MEGAMASERS

Eleven extragalactic H_2O masers[5,6,43] and one extragalactic maser in a radio line of H_2CO, from the peculiar galaxy IC 4553 (Ref. 7), have now been observed. The H_2O masers are observed in irregular, interacting or coalesced, Seyfert, and decayed spiral galaxies. The nuclei of these galaxies are active, and they have a high IR luminosity, but these conditions by themselves are not sufficient since the galaxy M82, for example, has a high IR luminosity and an active nucleus, but we do not observe an intense H_2O maser from it (the luminosity of the galaxy M82 is $L_{H_2O} \sim 1.5 L_\odot$). Accordingly, H_2O masers with a luminosity $L_{H_2O} \sim 10^2\text{–}5\cdot 10^2\ L_\odot$, which are observed from such galaxies as NGC 3079, NGC 1068, NGC 4945, and NGC 4258, are probably short-lived phenomena and thus exceedingly rare. Of the 36 "normal" spirals with a luminosity $L \sim 3\cdot 10^{10}\ L_\odot$, only two have exhibited an H_2O maser. In both the galactic and extragalactic H_2O sources, there is a relationship $L_{H_2O} \sim (10^{-7}\text{–}10^{-9}) L_{IR}$ (Refs. 44 and 45), and there are also similarities in the IR color temperatures (high 60/100-μm, 25/60-μm color temperatures and low 12/25-μm color temperatures).

The extragalactic H_2O masers have velocities differing from the centroid of the velocities of the mother galaxies; in, e.g., NGC 3079 the H_2O structures are shifted by -140 km/s, and in NGC 4258 the H_2O structures are shifted by -60 km/s, while the velocities of the OH structures agree with the systematic velocities of the galaxies. The velocity interval spanned by the H_2O maser lines is very large (up to 700 km/s in the galaxy NGC 1068). In the local galaxy, the record in this contest is held by the most powerful source, W 49, for which the velocity interval spanned by H_2O structures is ~ 500 km/s. It is pertinent to recall at this point that a kinematic interpretation of this phenomenon is presently regarded as most likely: Clouds are accelerated by a stellar wind or by the radiation pressure of a central star, as first suggested in Ref. 46. The similarity among the extragalactic sources is not complete here, since the high-velocity structures in the galactic sources have intensities about two orders of magnitude lower than those of the main structures. The extragalactic H_2O masers have a variability of a burst nature[43] (see Refs. 47 for more details regarding a burst in an Ori galactic source). So far, the primary result of the observations has been the measurement on VLA of the size of the H_2O emission region; this size does not exceed 1.3 pc in the galaxy NGC 4258 or 3.5 pc in NGC 1068 (these dimensions may be significantly smaller[48]). This fact forces us to reject the suggestion that 100–500 sources similar to W 49 are contributing to the observed luminosity, on the basis of the unacceptably high density of OB stars in the nuclei of these galaxies.[48] An upper limit on the density of OB stars in the nuclei of the galaxies M82 and NGC 253 is $< 3\ pc^{-3}$; the density of OB stars in the disk of our own galaxy is $\sim 10^{-4}\ pc^{-3}$ (see also Ref. 48). The absence of a significant number of OB stars causes serious energy difficulties for the radiation mechanism for the pumping[49] of H_2O, since the efficiency of this mechanism has been greatly overestimated, as was first pointed out by Strel'nitskiĭ.[50a] Since extragalactic H_2O masers have a huge luminosity ($\geqslant 10^{51}$ photons/s) and a small size, in contrast with OH megamasers, they are probably working in a regime of saturated gain, in which the intensity of the output emission does not depend on the intensity at the input. Using the very simple estimate

$$L = h\nu n_1 \Delta P \cdot V \qquad (10)$$

of the luminosity of a maser in saturated operation, where n_1 is the number of H_2O molecules in the 6_{16} upper signal level, and ΔP is the pumping rate, we can estimate the efficiency of the process which creates the inversion. In order to explain a luminosity $L_{H_2O} \sim 10^2\text{–}5\cdot 10^2\ L_\odot$, the quantity $n_1\Delta P$ would have to be in the interval $6\cdot 10^3\text{–}3\cdot 10^4\ cm^{-3}\cdot s^{-1}$, if the volume is, for example, $V \sim 4\cdot 10^{45}\ cm^3$ and if the number of maser structures is ~ 100 [the number of maser structures has been chosen arbitrarily, as has the size of the H_2O maser condensation ($\sim 10^{15}$ cm)]. Collisional pumping mechanisms[50] which have been proposed to explain the extremely powerful galactic H_2O masers W 49, W 51, etc., in which a two-temperature gas with $T_e \neq T_{H_2}$ and a degree of ionization $\sim 10^{-5}\text{–}10^{-6}$ is required in order to create the inversion, are capable in principle of explaining the observed characteristics of extragalactic H_2O masers. It seems to us that the extragalactic H_2O maser phenomenon is just as rich and diverse as the galactic phenomenon, and in the less-powerful sources, e.g., the galaxies M82 and IC10, a radiation

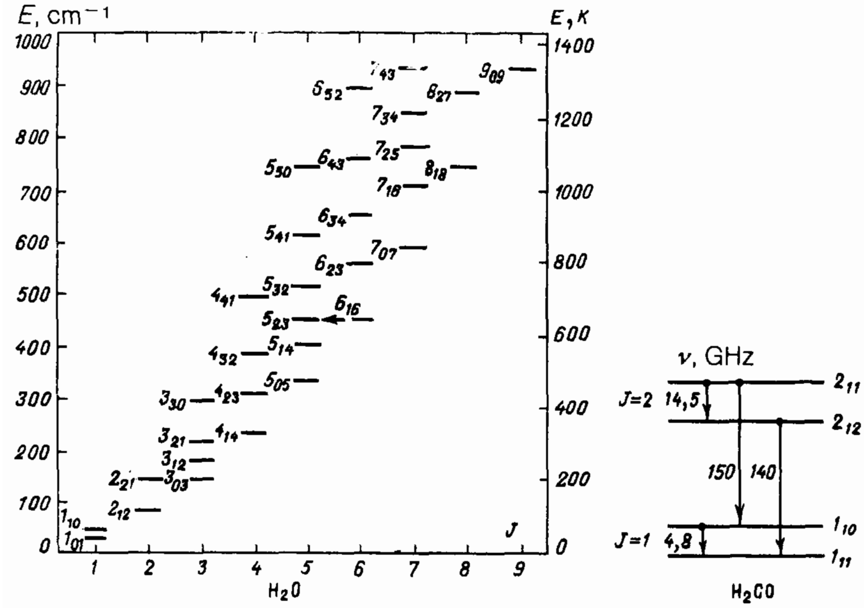

FIG. 2. Low-lying rotational levels of the H_2O and H_2CO molecules.

pumping mechanism with photons with $\lambda \approx 6.3\ \mu m$ must be operating, as proposed in Ref. 49, since there are substantial IR correlations[43] and a pronounced variability. Furthermore, as clouds collide with each other or with the surrounding envelope there might be a combination of radiation and collisional excitation.[51] In a pumping of this sort, kinetic energy of the moving clouds ("bullets") would be converted into internal energy of the gas, giving rise to a maser effect on H_2O molecules (in general, however, this situation is short-lived, as was pointed out in Ref. 51). An exceptionally important condition for reaching an understanding of the physics of extragalactic H_2O masers is to measure the individual sizes of the H_2O structures. For extragalactic sources, this can be done only by a composite space-ground interferometer[52] having a resolution $\leqslant(100\cdot10^{-6})''$. Such an interferometer should be implemented in the QUASAT and Radioastron projects. A careful study of the kinematics of H_2O masers (involving measurements of the statistical and orbital parallax) can refine the value of Hubble's constant.[52] We thus see that the only point that is clear about extragalactic H_2O masers is that in certain active galactic nuclei there is a high rate of outflow of matter which forms into clouds, and here the pumping condition $n_1\Delta P \sim 10^4\ cm^{-3}\cdot s^{-1}$ can be realized. Just what is feeding the phenomenon and just how remote these conditions are from the conditions in the nucleus of our own galaxy[53] require further study.

The megamaser in the $1_{10}\to1_{11}$ radio line of the H_2CO molecule ($\lambda \approx 6.2$ cm) which has been observed from the galaxy IC 4553 has a velocity centroid and a linewidth ($\Delta v \sim 169$ km/s) which are the same as those of the main radio lines of OH at a luminosity $L_{H_2CO} \sim 12L_\odot$ (Ref. 7). So far, this is the only example of an extragalactic maser involving the formaldehyde molecule, although absorption in the $1_{10}\to1_{11}$ line has been observed from the galaxies NGC 3079, NGC 253, NGC 4945, M82, etc. (see Ref. 7 and the bibliography there). In the local galaxy, maser radiation in a radio line of the H_2CO molecule has been observed from only two sources, with luminosities $L_{H_2CO} \sim 1.1\cdot10^{-6}L_\odot$ (Sgr B2; Ref. 54) and $L_{H_2CO} \sim 3.2\cdot10^{-8}L_\odot$ (NGC 7538; Ref. 55). Like the OH megamasers, the extragalactic masers in the H_2CO radio line have an extended structure (~ 30 pc), so their gain is extremely low: $\tau_{4.8GHz} \sim 1.5\times10^{-2}$, i.e., $\exp(\alpha l) \sim 1.015$. The pumping agent in the galactic H_2CO masers appears to be thermal emission (free-free transitions, $\lambda \approx 2$ mm) from compact H II regions[56]; i.e., a purely radiation pumping mechanism is operating under the condition $\tau_{2mm} < 1$. The physical reason for the pumping is that the induced transition $J = 2 \to 1$ to the upper level of the $J = 1$ state is faster than that to the lower level (Fig. 2). Since there is no observable flux of a thermal continuum from the galaxy IC 4553, Baan *et al.*[7] have carried out a model calculation for the possible pumping of an H_2CO maser by a nonthermal continuum for various H_2CO concentrations (the production and concentration of H_2CO molecules are discussed briefly in Ref. 56). The optimum value found for the ratio of the H_2CO concentration to the velocity gradient in the medium (a velocity gradient is required by virtue of the condition $\tau_{2mm} < 1$), at which the optical thickness in the $1_{10}\to1_{11}$ radio line reaches a maximum[7] ($\tau_{4.8GHz} \sim 2\cdot10^{-2}$), is $[n_{H_2CO}]/\partial v/\partial z \sim 10^{-4}$. As in the OH megamasers, the H_2CO molecules amplify the radio emission of the disk and the nucleus.

CONCLUSION

From this (far from complete) picture of the phenomenon of extragalactic megamasers we can draw some preliminary conclusions. The megamasers which operate on the OH molecule and the megamaser which operates on the H_2CO molecule amplify the radio emission of the disk and nucleus of certain IRAS galaxies. The OH megamasers are probably pumped by IR light with $\lambda \approx 35\ \mu m$ and $\lambda \approx 20\ \mu m$, and the H_2CO megamaser is most probably pumped by light at $\lambda \approx 2$ mm. Since these megamasers operate in an unsaturated regime, we would expect that any variability in the nucleus or disk would be amplified by a factor of $\exp(\alpha,l)$, i.e., that it would be possible to study the variability in the radio lines of the molecules. Since these galaxies are remote, an entire galaxy falls within the directional pattern of ground-based antennas; this circumstance is reflected in the broad-band nature and high power of the maser radio emission of these galaxies, since the entire interstellar medium or a large part of its disk is emitting.

It seems extremely likely that extragalactic maser radio emission will be observed from the CO molecule in the radio line $F = 0^- \to 1^+$ (3264 MHz) of the rotational ground state $J = 1/2$, although the conditions for observing this emission are fairly severe. With $N_{CH} \sim 10^{14}$ cm^{-2} (N_{CH_2} is the density of molecules along the line of sight), as was pointed out in Ref. 57, a degree of inversion $\sim 10\%$ would occur in an interaction of CH with IR light at $\lambda \approx 150$ μm at $n_{H_2} \sim 10^3$ cm^{-3} and $T \sim 30$–100 K. The value $\alpha l \sim 1$ in unsaturated amplification is reached over a distance ~ 1 kpc if $[n_{CH}]/[n_{CH_2}] \sim 10^{-8}$, $\Delta n \sim 10^{-6}$ cm^{-3}, and $\Delta v \sim 300$ km/s.

Near the active nuclei of certain spiral galaxies with a high rate of outflow of matter, probably only a collisional mechanism could satisfy the pumping condition $n_1 \Delta P \sim 10^4$ cm^{-3} s^{-1} for an H_2O maser. Clouds moving at a high velocity (~ 100 km/s) emit by a maser mechanism. The sizes of the individual H_2O clouds at a distance of several megaparsecs or more from the earth could be measured only by a composite space-ground interferometer with a resolution $\lesssim (100 \cdot 10^{-6})''$ in the future Radioastron and QUASAT experiments. These experiments will make it possible not only to cast light on the physical nature of H_2O masers but also to "peer into" active nuclei. Furthermore, a study of the kinematics of moving H_2O structures will serve as a new method for refining Hubble's constant.

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[1)] IRAS stands for "Infrared Astronomical Satellite."
[2)] As suggested by B. V. Komberg.

[1] W. A. Baan, P. A. D. Wood, and A. D. Haschick, Astrophys. J. Lett. **260**, 149 (1982).
[2] (a) W. A. Baan, A. D. Haschick, and J. T. Schmelz, IAU Circ. No. 3993, 1984; Astrophys. J. Lett. **298**, L51 (1985). L. Bottinelli, D. Fraix-Burnet, L. Gouguenheim, A. M. le Squeren, and I. Patey, IAU Circ. No. 4074, 1985. L. Bottinelli, D. Fraux-Burnet, L. Gouguenheim, I. Kazes, A. M. le Squeren, I. Patey, L. J. Rickard, and B. E. Turner, Astron. Astrophys. **151**, L7 (1985). L. Bottinelli, L. Gouguenheim, A. M. le Squeren, M. Dannefeld, and G. Paturel, IAU Circ. No. 4106 (1985). J. M. Chapman, R. J. Cohen, L. Pointon, L. Staveley-Smith, and S. W. Unger, IAU Circ. No. 4180 (1986). L. Bottinelli, L. Gougenheim, A. M. Squeren, J. M. Martin, M. Dennefeld, and G. Paturel, IAU Circ. No. 4231 (1986). R. P. Norris, J. B. Whiteoak, F. F. Gardner, D. A. Allen, and P. F. Roche, IAU Circ. **221**, 51 (1986). I. F. Mirable, IAU Circ. No. 4268 (1986). L. Bottinelli, L. Gouguenheim, A. M. Squeren, J. M. Martin, M. Dennefeld, and G. Paturel, IAU Circ. No. 4357, 4379 (1986). I. Kazes, I. F. Mirabel, and D. B. Sanders, IAU Circ. No. 4362 (1986). I. F. Mirabel, I. Kazes, and D. B. Saners, Astrophys. J. **324**, L59 (1988). (b) L. Staveley-Smith, S. W. Unger, R. J. Cohen, J. M. Chapman, and L. Pointon IAU Circ. No. 4248 (1986); Mon. Not. RAS **226**, 689 (1987).
[3] J. B. Whiteoak and F. F. Gardner, Astrophys. Lett. **15**, 211 (1973). Nguyen-Q-Rieu, U. Mebold, A. Winberg, J. Guibert, and R. Booth, Astron. Astrophys. **52**, 467 (1976).
[4] W. A. Baan, Nature **315**, 26 (1985).
[5] E. Churchwell, A. Witzel, W. Huchtmeier, I. Pauliny-Toth, J. Roland, and W. Sieber, Astron. Astrophys. **54**, 969 (1977).
[6] W. K. Huchtmeier, A. Witzel, H. Kuhr, I. I. Pauliny-Toth, and J. Roland, Astron. Astrophys. Lett. **64**, L21 (1978). P. M. Dos Santos and J. R. D. Lepine, Nature **278**, 34 (1979). F. F. Gardner and J. B. Whiteoak, Mon. Not. RAS **201**, 13 (1982). C. Henkel, R. Gusten, D. Downes, C. Thum, T. L. Wilson, and P. Biermann, Astron. Astrophys. Lett. **141**, L1 (1984). M. J. Claussen, G. M. Heiligman, and K. J. Ko, Nature **210**, 298 (1984).
[7] W. Baan, R. Gusten, and A. D. Haschick, Astrophys. J. **305**, 830 (1986).
[8] H. Weawer, D. R. W. Williams, N. H. Dieter, and W. T. Lum, Nature **208**, 29 (1965).
[9] S. Weinreb, M. L. Meeks, J. C. Carter, A. N. Barret, and A. E. E. Rogers, Nature **208**, 440 (1965).
[10] J. M. Moran, B. F. Burke, A. H. Barrett, A. E. E. Rogers, J. A. Ball, and J. C. Carter, Astrophys. J. Lett. **152**, L97 (1968).
[11] (a) C. H. Townes, in Fourth IAU Symposium, Manchester, 1955, H. C. van de Hulst, Ed., Cambridge Univ. Press, Cambridge, 1957, p. 92. (b) A. C. Cheung, D. M. Rank, C. H. Townes, D. D. Thornton, and W. J. Welch, Nature (London) **221**, 626 (1969).
[12] I. S. Shklovskiĭ, Astron. Zh. **26**, 10 (1949) (not translated).
[13] R. Genzel, D. Downes, M. H. Schneps, M. J. Reid, J. M. Moran, L. R. Kogan, V. I. Kostenko, L. I. Matveyenko, and B. Ronnang, Astrophys. J. **247**, 1039 (1981).
[14] M. J. Reid and J. M. Moran, Ann. Rev. Astron. Astrophys. **19**, 231 (1981). M. Elitzur, Rev. Mod. Phys. **54**, 1225 (1982).
[15] D. B. Sanders, N. Z. Scoville, Y. S. Young, B. T. Soifer, F. P. Schloerb, W. L. Rice, and G. E. Danielson, Astrophys. J. **305**, L45 (1986).
[16] M. A. Arakelyan, Astrofizika **10**, 507 (1974) [Astrophysics **10**, 321 (1974)].
[17] W. L. W. Sargent, Astrophys. J. **160**, 405 (1970). M. A. Arakelyan, É. A. Dibaĭ, V. F. Esipov, and B. E. Markaryan, Astrofizika 7, 177 (1971) [Astrophysics 7, 102 (1971)].
[18] S. W. Unger, J. M. Chapman, R. J. Cohen, T. G. Hawarden, and C. M. Mountain, Mon. Not. RAS **220**, 1 (1986).
[19] W. A. Baan and A. D. Haschick, Astrophys. J. **279**, 541 (1984). J. T. Schmelz, W. A. Baan, and A. D. Haschick, Astrophys. J. **321**, 225 (1987).
[20] R. Wielebinski, E. Wunderlich, U. Klein, and E. Hummel, in: Proceedings of the Conference "Star Formation in Galaxies," C. J. Lonsdale Persson, ed., California Inst. Techn., Pasadena, 1986, p. 589.
[21] (a) G. K. Miley and R. de Grijp, Preprint No. 65, Space Telescope Science Institute, Baltimore, 1985. (b) J. H. Fairclough, Mon. Not. RAS **219**, 1 (1986). (c) C. G. Wynn-Williams and E. E. Becklin, Astrophys. J. **308**, 620 (1986). (d) R. Chini, E. Kreysa, E. Krugel, and P. G. Mezger, Astron. Astrophys. **166**, L8 (1986).
[22] A. Lawrence, D. Walker, M. Rowan-Robinson, K. J. Leech, and M. V. Penston, Mon. Not. R. Astron. Soc. **219**, 687 (1986).
[23] W. C. Keel, in: Proceedings of the Conference "Star Formation in Galaxies," C. J. Lonsdale Persson, ed., California Inst. Techn., Pasadena, 1986, p. 661.
[24] D. B. Sanders, B. T. Soifer, G. Neugebauer, N. Z. Scoville, B. F. Madore, G. E. Danielson, J. H. Elias, K. Matthews, C. J. Persson, and S. E. Persson, in: Proceedings of the Conference "Star Formation in Galaxies," C. J. Lonsdale Persson, ed., California Inst. Techn., Pasadena, 1986, p. 411.
[25] B. E. Turner, Astrophys. J. **186**, 357 (1973). R. M. Crutcher, Astrophys. J. **234**, 881 (1979).
[26] (a) G. D. Watt, Mon. Not. RAS **212**, 93 (1985). (b) S. S. Prassad and W. T. Huntress, Jr., Astrophys. J. Suppl. **43**, 1 (1980).
[27] J. M. Brown, J. T. Houigen, K. P. Huber, J. W. C. Johns, I. Kopp, H. Lefebre-Brion, A. J. Merer, D. A. Ramsay, J. Rostas, R. N. Zare, J. Mol. Spectr. **55**, 500 (1975).
[28] M. H. Alexander and P. J. Dagdigian, Chem. Phys. **80**, 4325 (1984).
[29] (a) P. Andresen, G. S. Ondrey, and B. Titze, Phys. Rev. Lett. **50**, 486 (1983). (b) P. Andresen, G. S. Ondrey, B. Titze, and E. W. Rothe, J. Chem. Phys. **80**, 2548 (1984).
[30] L. J. Stief, B. Donn, S. Glicker, E. P. Gentieu, and J. E. Mentall, Astrophys. J. **171**, 21 (1972).
[31] H. Okabe, Photochemistry of Small Molecules, Wiley-Interscience, New York, 1978 [Russ. transl. Mir, 1981, p. 93].
[32] D. B. Sanders and I. F. Mirabel, Astrophys. J. Lett. **298**, L31 (1985). P. G. Mezger, R. Chini, E. Kreysa, and H. P. Gemund, Preprint No. 244, Max-Planck Institute fur Raidoastronomie, Bonn, 1984.
[33] (a) J. H. Black and A. Dalgarno, Astrophys. J. Suppl. **34**, 405 (1977). (b) C. Norman and J. Silk, Astrophys. J. **238**, 158 (1980). (c) P. M. Solomon, D. B. Sanders, and N. Z. Scoville, *in*: Proceedings of the IAU Symposium No. 84, W. B. Burton, ed., D. Reidel, Dordrecht, Holland, 1979, p. 35.
[34] E. F. Van Dishoeck and A. Dalgarno, Astrophys. J. **277**, 576 (1984).
[35] P. Andresen, Astron. Astrophys. **154**, 42 (1986).
[36] (a) C. Henkel, W. Batrla, and R. Gusten, Astron. Astrophys. **168**, L13 (1986). (b) C. Henkel, R. Gusten, and W. A. Baan, Bull. Am. Astron. Soc. **18**, 689 (1986); Astron. Astrophys. **185**, 14 (1987).
[37] (a) V. Bujarrabel, J. L. Destomber, J. Guibert, C. Marliere-Demuynck, Ngugen-Q-Rieu, and A. Omont, Bull. Am. Astron. Soc. **81**, 1 (1980). (b) M. Elitzur, Bull. Am. Astron. Soc. **62**, 305 (1978).
[38] V. V. Burdyuzha and D. A. Varshalovich, Astron. Zh. **50**, 481 (1973) [Sov. Astron. **17**, 308 (1973)]. W. H. Kegel and D. A. Varshalovich, Nature **286**, 136 (1980). S. Guilloteau, R. Lucas, and A. Omont, As-

tron. Astrophys. **97**, 347 (1981).
[39]M. M. Litvak, Astrophys. J. **156**, 471 (1969).
[40]J. L. Destombes, C. Marliere, A. Baudry, and J. Brillet, Astron. Astrophys. **60**, 55 (1977).
[41]J. M. Brown, J. E. Shubert, K. M. Evenson, and H. E. Radford, Astrophys. J. **258**, 899 (1982).
[42]M. Rowan-Robinson, in: Proceedings of the Conference "Star Formation in Galaxies," C. J. Lonsdale Persson, ed., California Inst. Techn. Pasadena, 1986, p. 133.
[43]C. Henkel, J. G. Wouterloot, and J. Bally, Astron. Astrophys. **155**, 193 (1986).
[44]J. G. A. Waterloot and C. M. Walsmley, Preprint No. 255, Max-Planck-Institute für Radioastronomie, Bonn, 1986.
[45]R. Genzel and D. Downes, Astron. Astrophys. **72**, 234 (1979). D. T. Jaffe, R. Gusten, and D. Downes, Astrophys. J. **250**, 621 (1981). A. F. M. Morwood and P. Salinari, Astron. Astrophys. **125**, 342 (1983).
[46]V. S. Strel'nitskiĭ and R. A. Syunyaev, Astron. Zh. **49**, 704 (1972) [Sov. Astron. **16**, 579 (1972)].
[47]V. S. Strel'nitskiĭ, Pis'ma Astron. Zh. **8**, 165 (1982) [Sov. Astron. Lett. **8**, 86 (1982)]. Z. Abraham, N. L. Cohen, R. Opher, J. C. Raphaelli, and S. H. Zisk, Astron. Astrophys. Lett. **100**, L10 (1981).
[48]M. J. Claussen and K. Y. Lo, Astrophys. J. **308**, 592 (1986).
[49]P. Goldreich and J. Kwan, Astrophys. J. **191**, 93 (1974).
[50](a) V. S. Strel'nitskiĭ, Interstellar Molecules. IAU Symposium, No. 87, B. H. Andrew, ed., D. Reidel, Dordrecht, Holland, 1980, p. 591. (b) V. S. Strel'nitskiĭ, Mon. Not. RAS **207**, 339 (1984). N. D. Kylafis and C. Norman, Astrophys. L. Lett. **300**, L73 (1986). G. T. Bolgova, S. V. Makarov, and A. M. Sobolev, Astrofizika **27**, (1988). [Astrophysics **27**, (1988)].
[51]J. C. Tarter and W. J. Welch, Astrophys. J. **305**, 467 (1986).
[52]J. Moran, Nature **310**, 270 (1984). V. V. Andreyanov, N. S. Kardashev, M. V. Popov, V. A. Rudakov, R. Z. Slysh, and G. S. Tsarevskiĭ, Astron. Zh. **63**, 850 (1986) [Sov. Astron. **30**, 504 (1986)].
[53]I. Gatley, T. J. Jones, A. R. Hyland, R. Wade, T. R. Geballe, and K. Krisciunas, Mon. Not. RAS **222**, 299 (1986).
[54]J. B. Whiteoak and F. F. Gardner, Mon. Not. RAS **205**, 27 (1983).
[55]D. Downes and T. L. Wilson, Astrophys. J. Lett. **191**, L77 (1974). J. R. Forster, W. M. Goss, T. L. Wilson, D. Downes, and H. R. Dickel, Astron. Astrophys. **84**, L1 (1980). A. H. Rots, H. R. Dickel, J. R. Forster, and W. M. Goss, Astrophys. J. Lett. **245**, L15 (1981).
[56]W. Boland and T. de Jong, Astron. Astrophys. **98**, 149 (1981).
[57]V. V. Burdyuzha, Preprint No. 720, Institute of Space Research, Academy of Sciences of the USSR, M., 1982.

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