CONNECTION BETWEEN REGIONS OF RECENT STAR FORMATION AND STELLAR ASSOCIATIONS

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The connection between regions of recent star formation and stellar associations is considered. It is established that H_2O maser sources, which are encountered in regions of recent star formation and are very characteristic objects for them, occur in stellar associations. It is proposed to divide the H_2O maser sources into two classes on the basis of their properties. The first class contains the H_2O masers in stellar associations, and the second those outside these regions. The luminosity function of the H_2O sources is constructed. Properties of maser sources in regions of star formation are considered, and their connection with surrounding objects is discussed.

1. Introduction

In recent years, astronomers have devoted much attention to investigations of dense and giant interstellar molecular clouds. An important part in the discovery and investigation of these formations is played by spectral radio astronomy, since in the optical region the absorption of waves in the clouds may be tens of magnitudes, so that the inner parts of these regions are inaccessible to optical observational methods, while in the infrared they are only partly accessible.

The investigations have showed that in many of the cases investigated in detail the dense clouds contain regions of active star formation. They have become known as Regions of Recent Star Formation. Mainly as a result of application of the spectral methods of radio astronomy, it has been possible to extend investigations to the earliest stages of star formation.

The gas—dust complex of the Orion nebula (Orion association OB 1)is the best known and best studied region of star formation. It is situated between the Perseus and Sagittarius spiral arms. The well-known Kleinman—Low (KL) nebula in this association is at a distance ≤0.2 pc from the stars of the Orion Trapezium. It contains a group of infrared sources. The infrared luminosity of the KL luminosity reaches $10^5 L_\odot$, while the linear dimension is less than 0.05 pc. In the neighborhoods of the infrared sources there are water vapor and hydroxyl masers, which are good indicators of star formation. Thus, there is no doubt that the KL region is a region of star formation in which an intensive process of star formation is taking place at this very time.

Whereas the gas—dust complex of the Orion nebula is an OB association in a region between spiral arms, the source W3 (the Cassiopeia association OB 6) is a representative of a region of star formation associated with a spiral arm. It is a large gas and dust complex in the Perseus arm. The source W3, together with the large H II regions IC 1848, IC 1805, and IC 1795, found in the OB association Cas OB 6. As in the case of the Orion association, OH and H_2O masers and point infrared sources are also observed in W3.

The difference between these regions of star formation is quantitative rather than qualitative.

It is of interest to study in more detail the relationships between regions of recent star formation, the characteristic linear dimensions of which are fractions of a parsec, and OB associations, whose diameters are measured in tens of parsecs. It must be borne in mind that the OB associations are unstable and for dynamical reasons must break up (the linear expansion velocity can reach 10 km/sec) during a time of the order of ten million years [1].

Another example of young star associations is provided by complexes containing

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dwarf variable stars of the type of T Tau. These associations have been called T associations. It has been established that there is a connection between OB associations and T associations. Namely, some OB associations contain T associations within them. The diameters of the T associations are much less than those of the OB associations. Sometimes a single OB association can contain several T associations; for example the association Ori OB 1 contains at least eight T associations.

We have given above examples in which the OB associations also contain maser sources (see also [2, 3]).

To elucidate the connection between regions of recent star formation and stellar associations on the basis of observational data, it is expedient to employ as characteristic indicators of the former sources in the H_2O maser radio line at wavelength 1.35 cm, since on the basis of many properties (radiation power, compactness, variability of the radiation, outburst activity, etc.) and as regards the extent to which they have been studied the H_2O masers occupy a particular place among the masers in other spectral lines of interstellar molecules.

2. The H_2O Maser Radio Line in Regions of Star Formation

The H_2O maser radio line was detected for the first time in 1968 in the H II region W49 [4]. At the present time, more than 280 maser sources situated in regions of star formation are known [5, 6].

Besides their occurrence in regions of recent star formation, water vapor masers are also observed in the following objects: cold stars of the spectral classes M3—M8 with a strong excess of radiation in the near infrared, IR/OH stars, and compact H II regions. Water vapor masers associated with other objects — Herbig—Haro (HH) objects, T Tau stars, and Herbig Ae/Be stars — have also been discovered. The masers associated with stars of the classes M3—M8 are related to the late stages of stellar evolution, while the masers associated with H II regions, HH objects, and other objects are associated with the early stages of evolution. The H_2O masers in regions of star formation are also distinguished by the fact that they are more intense and rapidly variable; in a number of cases they exhibit outburst activity (W49, Ori—KL, GGD 25, Sgr B 2) (see, for example, [7]). In addition, the line profiles of these masers are more complicated than of the masers that are associated with cold stars. For some H_2O sources, the components differ in radial velocity by more than 300 km/sec. Unresolved infrared sources are often observed in the neighborhood of the masers.

Genzel and Downes [8] proposed a classification of H_2O masers in regions of star formation, relating them to different stages of evolution. In the early stages, the H_2O masers associated with recently formed protostars radiate single lines. This class includes H_2O sources of low luminosity found in dark gas—dust clouds; as a rule, they are not associated with compact H II regions. In a later stage of development of a H_2O maser, the line profile has a complicated structure. These H_2O masers are separated spatially into low- and high-velocity components. The low-velocity details are as a rule approximately two orders of magnitude more powerful than the high-velocity details. The difference between the radial velocities is in the interval from several tens to hundreds of km/sec. There are always compact H II regions in the neighborhoods of masers with complicated profiles.

This class of objects includes most of the best studied H_2O masers (Ori—KL, W3, W49, W51, and others). Interferometric measurements (see, for example, [9]) show that the low- and high-velocity components are ejected from a single activity center; moreover, the ejection occurred approximately simultaneously. In the case of Ori—KL, the object IRC 2 is at the ejection center [10]. It should be noted that a division of the masers associated with stars of the class M into low- and high-velocity details is not observed.

Sandell and Olofsson [11] proposed a classification of H_2O masers without use of the evolutionary space status. Their class I includes masers associated with OB stars, with compact H II regions, and with OH masers. This category encompasses all the "classical" H_2O masers. The H_2O masers associated with stars of low and medium masses belonging to the Orion population form class II. These masers are not associated with compact H II regions and are near small emission nebulas in dark clouds (some of the Herbig—

Haro objects are found in precisely these regions).

However, in our view, such a classification of the H_2O maser sources leads to an artificial separation of the H_2O sources encountered in regions of star formation. Indeed, as was noted above, there is much in common between the H_2O maser sources associated with the various objects encountered in regions of star formation (compact H II regions, Herbig—Haro objects, etc.).

Since the presence of H_2O masers in many associations is important for understanding the evolutionary status of masers, it is expedient to divide the H_2O maser sources in a first step into the following two classes. The first includes the H_2O masers that are found in stellar associations, and the second the masers outside these regions. In this case, of course, there will be objects in the direction of which it will be impossible, because of the large absorption of light, to detect readily the presence of stellar associations. Therefore, in such cases it will be desirable to classify such sources on the basis of the properties of the maser objects themselves.

Of course, for such a classification of the H_2O masers homogeneity of the two groups of objects will unavoidably be lost. However, it appears to us that such a classification of the maser sources reflects more naturally the connection with the surrounding objects and the evolution.

3. Discussion of Observational Data

Comparison of the well-known lists of H_2O maser sources encountered in regions of star formation [5, 6] and catalogs of OB associations [12, 13] showed that many associations contain H_2O masers. Table 1, which contains a list of OB associations, gives successively the designation of the association, the number of regions of H_2O maser sources, and the number of known multiple systems of Trapezium types in the given association. Data on the connection between the multiple systems of Trapezium type and associations whose main stars belong to the spectral classes O-B were taken from [14—16]. To determine whether or not a given H_2O object belonged to a stellar association, we took into account not only coincidence of the coordinates but also identity of the distances. The kinematic distances are known for the majority of H_2O sources. The values of these distances were taken from [5, 8, 17—23]. Of course, they are relatively crude estimates.

It should be noted that as yet it is impossible to give a more or less complete list

TABLE 1. Stellar Associations Containing H_2O Sources.

№	Designation	N_{H_2O}	N_{Trap}
1	Cas OB6	5	2
2	Per OB2	4	1
3	Ori OB1	7	4
4	Gem OB1	2	—
5	Mon OB1	1	—3
6	CMa OB1	1	—
7	Vel OB1	1	3
8	Car OB1	1	5
9	Nor OB1	1	—
10	Sco OB2	2	—
11	Nor OB4	9	1
12	Ara OB1 b	9	1
13	Sgr OB5	1	—
14	Sgr OB1	1	1
15	Sgr OB6	3	2
16	Ser OB1	13	1
17	Vul OB1	3	1
18	Cyg OB1	1	1
19	Cyg OB2	1	—
20	Cyg OB6	1	2
21	Cep OB3	2	—
22	Cas OB2	3	1

of the maser sources connected with associations. The reasons for this are, first, that as yet a complete survey of the plane of the Galaxy in the H_2O line has not yet been made and, second, for some sources their distances are unknown. Nevertheless, on the basis of the already available data some interesting results can, in our view, be obtained.

The catalogs of maser sources are mainly compiled on the basis of surveys made by means of single radio telescopes whose angular resolution is usually several tens of seconds of arc.

The list of [6] contains 283 regions of H_2O maser sources with a flux density of more than 1 Jy. For 241 of them, we calculated the isotropic luminosity at wavelength 1.35 cm. In practically all the catalogs of maser sources, it is the flux density of only the strongest detail of the line profile that is given. It is therefore difficult to determine the integrated luminosity of a source. However, on the basis of the data of [8] it is easy to show that, on the average, the luminosity of the maximal detail will be of the order of a third of the integrated luminosity of the source. In this connection, to characterize the luminosity of a maser, we restricted ourselves to data on the luminosity (erg/sec) of the most intense detail of the profile, taking as half-width of the line 1 km/sec, the characteristic value for the majority of H_2O maser sources.

Out of 241 objects, 137 are at a distance up to 4 kpc. On the other hand, the stellar associations detected by the optical method are mainly distributed up to 4 kpc. Therefore, in the comparison of various parameters of samples of objects that do and do not occur in the associations, we shall restrict ourselves to objects to which the distance is less than 4 kpc.

A count showed that out of the 137 H_2O masers 72 (53%) occur in stellar associations. This number is a lower limit, since, first, not all OB associations closer than 4 kpc are found by the optical method; second, in the direction of many stellar associations H_2O observations have not been made. In particular, some of the objects in Westerhout's list of H II regions [24] are shown on the basis of many criteria to be members of OB associations, but the large optical absorption in the direction of these objects does not permit detection of the associations. If such objects are taken into account, then it is found that of the 137 regions of H_2O emission 94 (~70%) occur in OB associations.

In [25], observations in the H_2O line were made in the direction of some stellar associations. The H_2O source detection percentage in this study was not high (~15%). In particular, maser sources were not discovered in the directions of the associations Ori OB 2, Mon OB 2, Cep OB 4. On the basis of the results of this study, some authors have drawn the incorrect conclusion that H_2O maser sources are seldom encountered in associations (see, for example, [17]), despite the fact that many H_2O sources observed in the direction of known associations were already known, even though the question of their belonging to the associations was not considered.

Indeed, according to the catalogs of maser sources observations in the H_2O line were made in the direction of about 30 known associations, in 22 out of which (73%) H_2O sources were found (Table 1). We note also that these observations cover only a small part of the volume of the associations. Thus, in each association in which water vapor maser sources are found their number is on the average about three.

4. Luminosity Function of Maser Sources

Figure 1 gives luminosity functions of H_2O masers. The upper histogram is the luminosity function for the 241 objects (N_t). Also given are the luminosity functions for the objects for which: a) there is more than one detail in the line profile (N_c), b) the line profile consists of a single detail (N_s). In the upper right corner we give the mean value of the logarithm of the luminosity and its standard deviation for each group. It is readily seen that the sources for which a complicated profile is observed have much higher luminosities than the objects with simple spectrum. The same dependences for the members of stellar associations and objects outside these regions, and also for all objects for which the distance is less than 4 kpc are given in Figs. 2 and 3, respectively. It can be seen that the objects in the OB associations are on the average 2.5 times more powerful than the objects outside them.

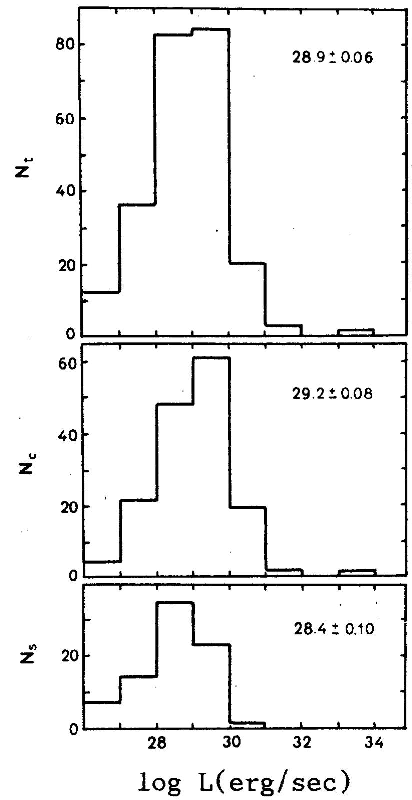

Fig. 1. Luminosity distribution of the number of H_2O maser sources. The mean value of the logarithm of the luminosity and its standard deviation are given in the top right corner.

These dependences of the numbers of H_2O sources on the luminosity can be characterized as follows. A decrease in the number of sources at large values of the luminosities indicates the absence of H_2O masers with log L > 34. With regard to the decrease in the number of sources at low values of the luminosity (log L ≤ 28.0), this is obviously mainly due to observational selection. This can be seen from the data of Table 2, which gives the distribution of the number of maser sources as a function of the luminosity and distance. It can be seen that for high values of the luminosity (log L > 28.0) the sources whose distances are greater than 1.0 kpc make a much larger contribution to the luminosity function than the objects with D ≤ 1.0 kpc. At the low end of the luminosity function, the contributions of the objects with D ≤ 1.0 kpc and D > 1.0 kpc are approximately the same, this being, as has already been noted, a consequence of observational selection. Indeed, if it is assumed that the maser sources are distributed uniformly in the plane of the Galaxy, then the number of objects of equal luminosity whose flux density is below the detection threshold of a radio telescope must be greater in a large volume than it is in a smaller volume. Therefore, if we know a total of 22 sources with 25.0 ≤ log L ≤ 28.0 and D ≤ 1.0 kpc, then the number of objects with the same luminosity for D ≤ 4.0 kpc must be approximately 350. On the basis of these results, and taking the

TABLE 2. Distribution of Maser Sources with Respect to Luminosity and Distance.

	log L≤28.0		28.0≤log L≤29.0	
	≤1.0 kpc	>1.0 kpc	≤1.0 kpc	>1.0 kpc
N_t	22	28	5	50
N_c	12	17	4	32
N_s	10	11	1	18

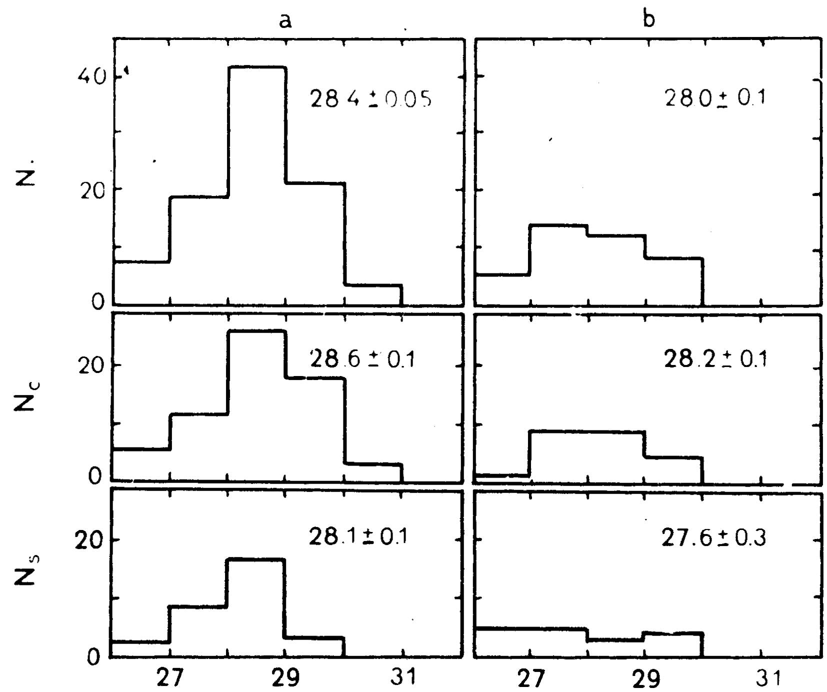

Fig. 2. Luminosity distribution of the number of H_2O maser sources: a) for members of stellar associations, b) for objects outside these regions.

TABLE 3. Luminosity Distribution of Maser Sources with D ≤ 1 kpc.

log L	25.0-25.9	26.0–26.9	27.0–27.9	28.0–28.9	⩾ 29.0
Members of OB associations	—	8	4	3	1
Objects outside OB associations	1	6	4	1	—
Total	1	14	8	4	1

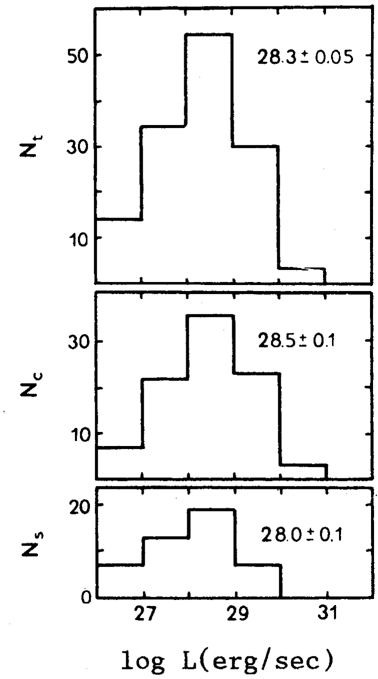

Fig. 3. Luminosity distribution of the number of H_2O maser sources whose distances are less than 4 kpc.

radius of the galactic disk to be 15 kpc, one can estimate the total number of H_2O maser sources in the Galaxy with luminosity $25.0 \leq \log L \leq 34.0$. The calculations show that the number of such objects must be about 5000. However, bearing in mind that they are actually distributed nonuniformly in the plane of the Galaxy [6], the expected number of objects will be between 2000 and 2500. In [26], the number of H_2O masers was estimated at ~2000.

This prompts the following question: Were all the masers in the regions of star formation formed in OB associations? We make a rough estimate. At the present time, 16 OB associations are known in the neighborhood of the sun (up to distances of 1 kpc). Therefore, if they are distributed nonuniformly, the total number of such associations in the Galaxy must be approximately 1000. Then the number of maser sources in associations (assuming three masers in each) is ~3000, a value that is entirely sufficient to explain the origin of all these sources in the Galaxy.

The absence of objects with $\log L < 25.0$ is due to the fact that either such sources simply do not exist or the sensitivity of modern radio telescopes is insufficient for the detection of such faint objects. The second explanation appears to us more probable. Indeed, the sensitivity of modern spectral observations at wavelength 1.35 cm makes it possible to detect only objects with flux density greater than 1 Jy. Therefore, objects with $\log L < 25.0$ are accessible for observations only at short distances in the neighborhood of the sun (~300 pc).

Table 3 gives the distribution of maser sources with $D \leq 1$ kpc as a function of their luminosity. Examination of the objects with $\log L \geq 27.0$ shows that out of 13 sources eight are members of known OB associations (out of these eight objects, four also belong to the T associations Ori T 2, Mon T 1, and Sco T 1); out of the remaining five, three are near compact H II regions, and two are associated with compact H II regions of high density without appreciable radio emission in the continuum.

In the case of objects with $\log L < 27.0$, eight of 15 sources are members of OB associations (and five of these belong simultaneously to the T associations Ori T 2, Ori T 3, Ori T 8, and Sco T 1); out of the remaining seven, three are associated with compact H II regions and the remainder with faint stars belonging to the Orion population (two of these objects are members of the T associations Tau T 2 and Mon T 3). In this connection, it should be noted that, in accordance with the results of [11, 26, 27], masers associated with stars of relatively low luminosity belonging to the Orion population are weak sources, and, at the same time, maser radiation is not detected ($\log L < 25.0$) in the case of the overwhelming majority of these stars. On the other hand, the main fraction of these stars are members of T associations.

Therefore, on the basis of the above it can be concluded that the absolutely fainter maser sources in the regions of star formation are most probably encountered in T associations.

5. Discussion

a) In accordance with the catalogs of H_2O maser sources [5, 6], only 13 sources are known at high galactic latitudes ($|b| > 15°$), although observations were made in the direction of more than 40 objects. All 13 sources detected at these latitudes are members of the stellar associations Ori OB 1, Per OB 2, and Sco OB 2. Besides these associations, there is, in accordance with [12], one further association with $|b| > 15°$ that is known (Lac OB 1). However, so far as we know, practically no observations in the H_2O line have been made in the direction of this association. It will be interesting to make such observations, especially since Lac OB 1 is one of the associations closest to the sun. The data we have given suggest strongly that H_2O maser sources (relating to early stages of stellar evolution) with $|b| > 15°$ are found exclusively in stellar associations or in open clusters. In this connection, it is not without interest to note that attempts to detect H_2O radiation from globular clusters have been unsuccessful [28].

b) It is well known that multiple, Trapezium type systems are often found in OB associations [14]. For example, out of 88 associations, 36 (40%) contain such systems. According to our data (see Table 1), almost 70% of the associations that contain H_2O maser sources simultaneously have multiple, Trapezium type systems, and it is only in 30% of these associations that Trapezium type systems are absent. On the other hand, among the associations that do not contain H_2O masers only about 30% contain Trapezium type systems. Thus, the presence of maser sources and the presence of Trapezium type systems in associations are strongly correlated.

In accordance with [29], multiple, Trapezium type systems are dynamically unstable and must fairly rapidly break up. Calculations show that their breakup time is of the order of $2 \cdot 10^6$ yr when the system has negative total energy. But if the total energy of the system is positive, the breakup time is of order 10^5 yr or less. Therefore, irrespective of the sign of the total energy, multiple, Trapezium type systems are among the youngest objects in stellar associations.

The existence of a large number of multiple, Trapezium type systems in stellar associations indicates that the young O-B stars in them are born in groups and not in isolation.

According to the estimates in the literature (see, for example, [17]), the duration of the phase of maser emission of H_2O molecules in regions of star formation is, on the average, 10^5 yr. Therefore, the H_2O sources and stellar trapezia must often be formed practically simultaneously or with only a small difference in time.

c) A remarkable feature of the regions of water vapor maser sources found in stellar associations is that in them one often observes nonstationary phenomena in the form of bursts of radiation, ejections, and expansion. Indeed from this point of view the most interesting H_2O sources among the objects that have distances less than 4 kpc are in associations. For example, the sources Ori—KL, W3, Cep A, NGC 2071, NGC 2024, NGC 1333, and some others are members of stellar associations.

We consider in somewhat more detail the observed manifestations of nonstationary phenomena in the maser sources.

In the first place, it is natural to consider the features of the object Ori—KL, since this source has been investigated in more detail and it exhibits practically all forms in which nonstationarity is manifested.

As we said in Sec. 2, at least two forms of H_2O sources exist in Ori—KL: low- and high-velocity sources [10, 30]. In the cited papers it is noted that these components were most probably ejected from the infrared object IRC 2. The low-velocity components are moving away from IRC 2 with velocity 18 km/sec, while the velocity of separation of the high-velocity components is less definite (30—100 km/sec).

Another manifestation of nonstationarity of the source Ori—KL in the H_2O line is its outburst activity. An outburst was first observed in this region of masers in 1979 at radial velocity 8 km/sec [31]; during it, the radiation power increased by almost 1000 times ($2 \cdot 10^6$ Jy). Further observations showed that, after a certain decay, the radiation power again increased, to $7 \cdot 10^6$ Jy in 1984 [7, 32].

The paper [33] gives a list of nine H_2O maser sources that exhibit variability during intervals of the order of a few days. The list includes all such objects known in the literature up to the middle of 1985. It is interesting that seven of the nine objects are members of known associations. All the indications are that the other two, W75 and W49, also belong to complexes, which are probably associations. According to [34], in W3 OH an outburst was observed, the rise of the radiation lasting just 5.5 days.

The source Cep A [33] exhibits correlated outbursts of the radiation of several components of the line, like W49 [7, 35].

According to [5], the overwhelming majority of maser sources in regions of star formation are associated with point infrared objects.

Thus, summarizing, it can be said that H_2O maser sources in stellar associations (class I) are rapidly variable, often form clusters of low- and high-velocity components ejected from certain centers, exhibit outburst activity, and are associated with infrared objects, compact H II sources, OH masers at frequencies 1665 or 1667 MHz, massive OB stars or T Tau type stars, etc.

Such masers, belonging to W49, W51, and other such formations, should also be included in class I, since on the basis of the properties of the H_2O maser radiation they are typical representatives of the first class, although in the direction of these complexes it is impossible to observe individual stars in them, so that one cannot make a definitive inclusion of these complexes in the list of stellar associations.

At the same time, we should not rule out the possibility that in some comparatively old associations, in which the process of star formation has practically stopped, maser sources may simply be absent. One such association may be Per OB 1, in which neither H_2O masers nor H II regions are observed.

In class II we must include in the first place the H_2O masers associated with stars of late spectral classes with strong radiation in the near infrared, IR/OH masers, and certain others that are not included in associations.

In respect of the properties of the H_2O radiation, supergiants of the class M are similar to the maser sources encountered in regions of star formation (see, for example, [36]). In addition, cold supergiants can occur in OB associations and, probably, are very young stars [37]. In particular, the variable star VY CMa, a supergiant of the class M3—M5, is the main star of the close Trapezium type system ADS 6033 and a powerful source of water vapor maser radiation.

It should be emphasized that on the average the intensity of the class I masers exceeds that of the class II masers by 1000 times.

In conclusion, we note that further study of the connection between H_2O masers and OB associations may cast new light on the cosmogonic processes that take place in the latter. We now know that in stellar associations we observe systematically regions whose age and linear dimensions are tens of times smaller than they are for associations. Their number includes clusters and trapezia of young stars, intense <u>maser and infrared sources</u>, Herbig—Haro objects, and other peculiar sources — in other words, "regions of recent star formation." Thus, the above facts indicate that, first, not all the stars in an association arise simultaneously and, second, the formation of individual groups may occur in comparatively small regions compared with the volume of the association [38].

6. Conclusions

The main results of this paper are as follows:

a) Regions of recent star formation, characteristic indicators of which are H_2O masers, are mainly observed in stellar associations.

b) The presence of maser sources and the presence of multiple, Trapezium type systems in associations are strongly correlated.

c) Practically all forms of nonstationarity are manifested in the H_2O maser sources observed in stellar associations. On the average, these sources are more powerful than the objects outside such associations.

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