OH/IR stars as signposts for ancient starburst activity in the Galactic center

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Abstract. A recent survey has considerably increased the number of OH/IR stars known within 50 pc of the Galactic center (GC). The distribution of expansion velocities of the circumstellar shells of these stars shows an unexpectedly narrow peak around 19 km/s at the high end tail. From this, we conclude that a large fraction of stars was formed in an epoch of enhanced star formation at least one Gyr ago. Thus one can distinguish three different groups of stars in the direction of the GC: an old bulge-like population, a group of relatively young stars formed from continuously infalling gas, and a shrinking population of low-mass stars that formed in an isolated era - probably a starburst.

1. Introduction

Although the Galactic center region (GC) is totally obscured in the optical, individual stars can be observed at infrared wavelengths (IR). Because the GC is located at about 8 kpc (Reid 1993), stars that are studied in general are the very IR-luminous massive objects; mostly red and blue supergiants. These stars have characteristic life-times of less than a few tens of million years. Conclusions derived from these studies, e.g. on stellar abundances and star formation history in the GC, thus only reflect the most recent developments in the GC region, i.e. within the last ≈ 100 Myr.

Stars of low and intermediate mass, with ages that are much larger than 100 Myr (up to $\sim$ 15 Gyr), should contain information on much longer time scales. However, not only are these stars intrinsically weak in the IR, the field in the GC is crowded with such objects. An exception to both constraints forms the sample of OH/IR stars. After passing the main-sequence and red giant branch stages, an average star ($\sim$ 1-7 $M_\odot$) may become an OH/IR star just before it transforms into a planetary nebula (Iben 1991). It is then in an evolutionary very short-lived stage ($\sim 10^5$ yr) of high luminosity ($L \gtrsim 5\,000\ L_\odot$) and heavy mass-loss ($10^{-6}$-$10^{-4}$ $M_\odot$/yr) on the asymptotic giant branch (AGB). The matter lost by the central star resides in an expanding circumstellar envelope that re-radiates the absorbed variable ($200 < P < 2000$ days) stellar emission in the IR. This IR radiation is easily observed. Moreover, many of the envelopes around AGB stars form maser emission - in particular the characteristic 1612 MHz OH maser line, which is bright and easily recognizable (e.g. Habing 1996).

We have followed up the pioneering 1612 MHz surveys in the GC, done by Habing et al. (1983), Lindqvist et al. (1992a) and van Langevelde et al. (1992), with a sensitive search for OH/IR stars within 50 pc of the GC (Sjouwerman et al. 1998a). During the analysis of the new sample of OH/IR stars, we were struck by the distribution of expansion velocities ($v_{\rm exp}$) of the circumstellar envelopes. It is unlike any other distribution of samples elsewhere in the Galaxy (Sect. 2, Fig. 1), and has led us to re-analyze the path of Lindqvist et al. (1992b; Sect. 3). We conclude that we have found the remnants of an epoch of enhanced star formation, a starburst, more than one Gyr ago (Sect. 4). Early reports on this subject appeared in Sjouwerman (1997) and Sjouwerman et al. (1998b).

2. OH/IR stars in the Galaxy and the GC.

Since the discovery of OH/IR stars in the late 1960's, many surveys have been carried out in all parts of the Galaxy and the Large Magellanic Cloud (LMC). In particular, surveys after 1983 exploited the highly successful predictive property of the IRAS two-color diagram (Olnon et al. 1984, and e.g. Eder et al. 1988, te Lintel Hekkert et al. 1991, Blommaert et al. 1993). In regions where IRAS suffered from confusion (in the Galactic plane and bulge), the IRAS survey has been complemented by "blind" 1612 MHz surveys (e.g Lindqvist et al. 1992a, Blommaert et al. 1994, Sevenster et al. 1997). The line-of-sight velocity of each OH/IR star ($v_{\rm los}$) is easily measured as the *average* of the blue and red Doppler shifted 1612 MHz OH emission peaks from the expanding shell. In addition, the *difference* in velocity of the blue and red shifted peak ($2 \times v_{\rm exp}$) is a physical property related to the underlying star. Furthermore, a distance can be determined for some stars by measuring the angular size and the phase-lag between the blue and red shifted peak (e.g. Herman & Habing 1985). It is the combination of these properties that make OH/IR stars excellent probes to study the Galaxy.

In summary, the study of samples of OH/IR stars in the Galaxy have shown a statistical correlation between the $v_{\rm exp}$ and the age of the OH/IR stars (e.g. Baud et al. 1981). The age of the star, the time it takes to reach this very specific OH/IR stage in its evolution, is related to the main-sequence mass that determines the luminosity on the AGB, and its metallicity as reflected in the dust-to-gas ratio δ of the shell. The *average* age of a sample is also reflected statistically by the Galactic distribution and velocity dispersion of the samples: the older, the more spread out in phase-space.

Lindqvist et al. (1992b) have analyzed a sample of $\sim$ 150 OH/IR stars located within 200 pc of the GC (Lindqvist et al. 1992a). Statistically they found a difference in spatial and kinematic distribution between samples of OH/IR stars with low and high expansion velocities. The high expansion velocity objects ($v_{\rm exp} > 18$ km/s) are spatially much more concentrated to the GC (and plane) than the objects with $v_{\rm exp} < 18$ km/s. In addition, the high $v_{\rm exp}$ stars show a rapid rotation around the center, whereas the low $v_{\rm exp}$ group is dynamically very relaxed and scattered in both velocity and sky distribution. This division in groups of stars with high and low expansion velocities in the GC is analogous to other samples of OH/IR stars in the Galaxy (e.g. Baud et al. 1981). Also here, the stars with high $v_{\rm exp}$ are on average more massive and younger than the stars in the low $v_{\rm exp}$ group. Sevenster et al. (1995) drew the same conclusion from a dynamical analysis without explicitly splitting the sample of OH/IR stars into two according to $v_{\rm exp}$. From the tight rotation they even suggest that the high $v_{\rm exp}$ group formed in a distinct event. However, this view is contradicted by Serabyn & Morris (1996) who argue that the (young, massive OH/IR) stars were formed from separate infalling molecular clouds.

Apart from $v_{\rm exp}$, one would expect that other intrinsic physical properties also show statistical differences between both groups in the GC. However, recent attempts to find statistical differences, mainly in $M_{\rm bol}$, between groups with $v_{\rm exp} < 18$ km/s and $v_{\rm exp} > 18$ km/s have not been very convincing (e.g. Blommaert et al. 1998, Wood et al. 1998). The division in expansion velocities smaller and larger than 18 km/s, which has been used in almost every analysis of the sample in the GC, was chosen by Lindqvist et al. (1992b) simply to divide the sample into equally sized groups. In Sect. 3 we will show that this picture changes drastically if one does not require two roughly equal groups.

Qualitatively, the OH/IR star phenomena is generally well understood. The exact driving force of the mass-loss mechanism is still under investigation, but after matter escapes from the star it cools down, and dust and molecules start to form. The dust gets accelerated by the absorbed stellar radiation pressure, as quantified by the bolometric luminosity or magnitude of the star (L_*, $M_{\rm bol}$). The accelerated dust in turn is responsible for transferring momentum to the gas molecules. The particles reach a maximum velocity far away from the star : the expansion velocity of the envelope or shell. It is this (gas) velocity $v_{\rm exp}$ that we measure from the 1612 MHz OH masers at about 1000-10 000 AU from the central star. Clearly, strong radiation pressure results in large acceleration of the dust. Because the dust entrains the gas, the dust-to-gas ratio (δ), also influences the value of $v_{\rm exp}$. Typically one measures $v_{\rm exp} = 15$ (± 10) km/s. It can be shown that (Habing et al. 1994)

$$v_{\rm exp}^2 \propto \delta \cdot \sqrt{L_*} \; . \tag{1}$$

Samples of OH/IR stars in general consist of a mix of old low mass-stars, and younger, more luminous massive stars. Also, stars of similar mass may have different metallicities due to different amounts of recycled stellar material in the star. The samples of OH/IR stars found in the Galactic bulge and

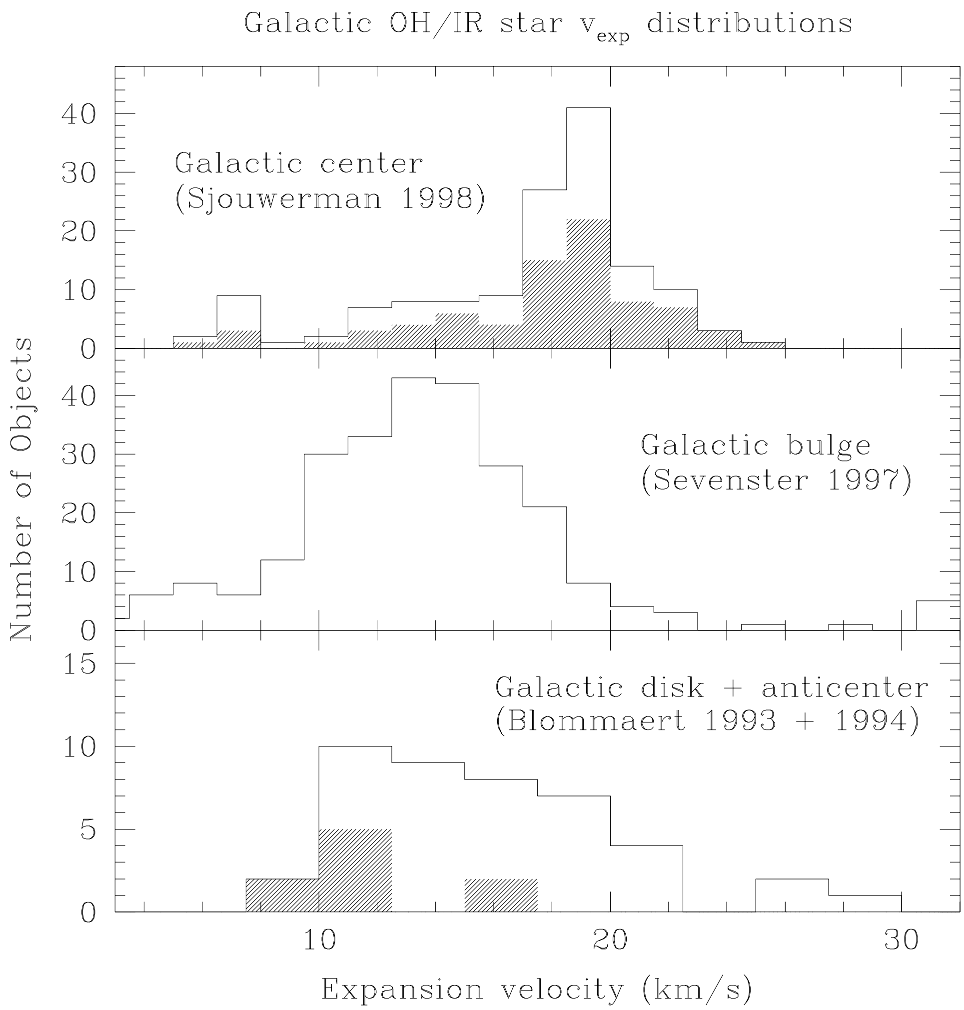

Figure 1. Expansion velocity distribution for OH/IR stars in the Galactic center (top frame, Sjouwerman et al. 1998a), the Galactic bulge (middle, Sevenster et al. 1997) and the combined Galactic disk and anticenter (bottom, Blommaert et al. 1993 and Blommaert et al 1994). In the bottom frame the shaded part shows the anticenter data, the histogram is for the combined sets. The shaded histogram in the top panel depicts the fraction of the stars in the bin for which a bolometric magnitude $M_{\rm bol}$ has been measured (Jones et al. 1994, Blommaert et al. 1998, Wood et al. 1998). For example, of the 41 stars in the bin with $v_{\rm exp} = 19$ km/s, 22 stars have a measured $M_{\rm bol}$. Note that this shaded histogram itself does not show any reference to the value of $M_{\rm bol}$ of the star, just that it is available. Because the shape of the shaded histogram in the top frame follows the histogram itself at about a 50% level, we may assume that the measured values and range in $M_{\rm bol}$ in each bin *roughly* represent the values and range in $M_{\rm bol}$ for all the stars with $v_{\rm exp}$ values of that bin.

disk+anticenter therefore show a wide distribution in $v_{\rm exp}$. The tail toward higher $v_{\rm exp}$ in the disk distribution can be understood in terms of more young, massive, and relatively metal-rich OH/IR stars compared to the bulge. Furthermore, for equally bright anticenter stars (shaded in the bottom frame of Fig. 1), the low metallicity causes the average $v_{\rm exp}$ to be significantly lower than for disk and bulge stars (e.g. Blommaert et al. 1993, Blommaert et al. 1994, and Wood et al. 1992 for LMC stars).

However, the distribution of $v_{\rm exp}$ of the sample of $\sim$ 140 OH/IR stars within 50 pc of the GC (Sjouwerman et al. 1998a) shows an unexpectedly narrow and high peak around the relatively high value of $v_{\rm exp}$ = 19 km/s. We are not aware of any physical phenomenon, such as an interstellar pressure or density field, that can transform e.g. a distribution similar to that of the bulge into that of the GC without decreasing all values for $v_{\rm exp}$. There must be relatively many stars with $v_{\rm exp} \approx 19$ km/s. Because the OH/IR stars in the GC are not more luminous than bulge stars, on average the stars in the GC have high (but unknown) metallicity (Eq. 1, Habing et al. 1994). But more importantly, with a similar range in $M_{\rm bol}$ (or L_*) as the bulge, the OH/IR stars in the GC have a very narrow distribution on top of a broad and roughly constant distribution. We identify the broad and constant distribution with the general mix of stars as also found in e.g. the disk. We observe that there is an over-abundance, or excess of stars with $v_{\rm exp} \approx 19$ km/s. We will refer to these stars as "the excess stars". Assuming Eq. 1 also holds for the GC, a narrow peak in $v_{\rm exp}$ for the excess stars can only exist if for a large fraction of the excess stars that form the peak, *either* the effects of metallicity and luminosity <u>cancel out</u>, *or* the <u>range</u> in <u>both</u> δ and L_* is <u>small</u>.

3. Orbital angular momentum and physical properties

One can almost immediately reject the explanation of cancelling effects of δ and L_*. It is true that δ and L_* are slightly anti-correlated (Vassiliadis & Wood 1993), but when one wants to explain the narrow peak by an overlap of the young, massive stars with the old, low mass stars, one has to assume that the low mass stars are considerably more metal-rich than the high mass stars (Eq. 1). This is in contradiction to what is generally found. Furthermore, the effect of cancelling δ and L_* should be *exactly the same* for all excess stars - otherwise the $v_{\rm exp}$ distribution would be broader due to the strong influence of δ on $v_{\rm exp}$.

Both Lindqvist et al. (1992b) and Sevenster et al. (1995) found that a major difference between the two groups is the rotation around the GC: the rotation of the high $v_{\rm exp}$ group is much more tight than for the group with $v_{\rm exp} < 18$ km/s. Actually, the slight rotation found in the low $v_{\rm exp}$ group is almost entirely due to including stars with $16.5 < v_{\rm exp} < 18$ km/s. It is unfortunate that Lindqvist et al. (1992b) chose $v_{\rm exp} = 18$ km/s to split the sample, because this is exactly where the excess stars also split into both the low and high $v_{\rm exp}$ groups. Thus, the "non-rotating group" has been polluted by the rotation of excess stars.

The increase in rotation around the GC with $v_{\rm exp}$ can be investigated by the contribution of each star to the cumulative sum of the total angular momentum of the sample. We show a measure of the angular momentum along the rotation axis of the Galaxy as function of $v_{\rm exp}$ in Fig. 2. It is the normalized sum over all

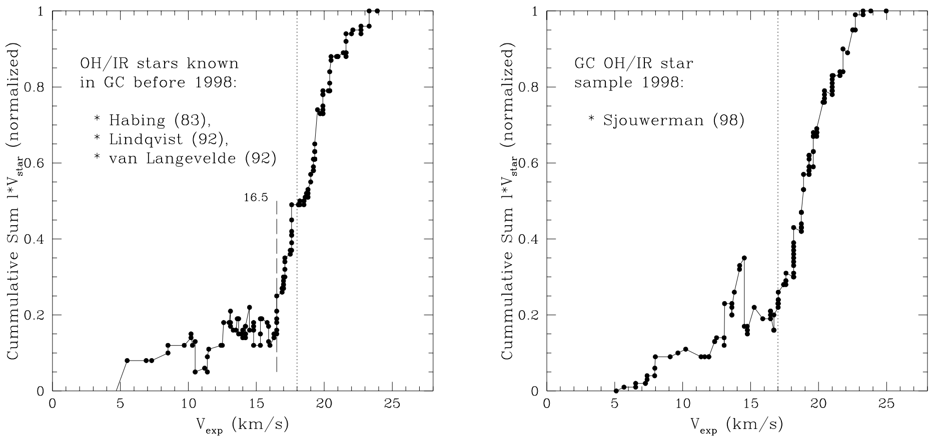

Figure 2. Normalized cumulative sum of $l \times v_{\rm los}$ as function of $v_{\rm exp}$. Left the OH/IR stars within 200 pc from the GC known from Habing et al. (1983), Lindqvist et al. (1992a) and van Langevelde et al. (1992). For most of these stars bolometric magnitudes and periods have been determined. Right the new sample of stars within 50 pc of the GC (Sjouwerman et al. 1998a). By dividing in two groups at $v_{\rm exp}$ = 18 km/s, Lindqvist et al. (1992b) included part of the rotating high $v_{\rm exp}$ group into the non-rotating low $v_{\rm exp}$ group. A division at $v_{\rm exp} \approx 16.5$ km/s would have been more proper. In both figures, there is a clear transition at $v_{\rm exp} \approx 17$ km/s. Deviations from the general trend at 11 and 14 km/s are due to high velocity stars ($v_{\rm los} \ll -200$ km/s).

stars, ranked according to increasing $v_{\rm exp}$, of $l \times v_{\rm los}$ (with l the Galactic longitude). For low $v_{\rm exp}$, the stars are dispersed over the $(l, v_{\rm los})$-diagram; individual contributions will be positive or negative (prograde or retrograde rotation) and no net rotation is expected. On the other hand, in the case of (prograde) rotation there is a strong correlation between l and $v_{\rm los}$. For the high $v_{\rm exp}$ one would expect the cumulative sum to accumulate.

It is clear from Fig. 2 that there is a sharp transition at $v_{\rm exp} \approx 17$ km/s. Below that value, the cumulative sum roughly hovers around a constant value indicating small or no net rotation. For comparison, for the IRAS based sample of te Lintel Hekkert et al. (1991), this value is $v_{\rm exp} = 13.5$ km/s. From both Fig. 1 and Fig. 2, we conclude that the low $v_{\rm exp}$ group should be characterized as stars with $v_{\rm exp} < 17$ km/s. Taking into account the steep drop-off at $v_{\rm exp} = 20$ km/s (cf. the rise at $v_{\rm exp} = 17$ km/s) in Fig. 1, we define the high $v_{\rm exp}$ group as stars with $v_{\rm exp} > 20$ km/s. The stars with intermediate $v_{\rm exp}$, the group with $17 < v_{\rm exp} < 20$ km/s, should be examined separately. From Fig. 2, a conclusion on kinematics for all three groups can be drawn immediately. Both the high and intermediate $v_{\rm exp}$ groups rotate rapidly, whereas the rotation of the sample of low $v_{\rm exp}$ stars is insignificant. With a slightly different definition of the high and low $v_{\rm exp}$ groups, we thus confirm the results of Lindqvist et al. (1992b) and Sevenster et al. (1995) on the dynamics of both groups.

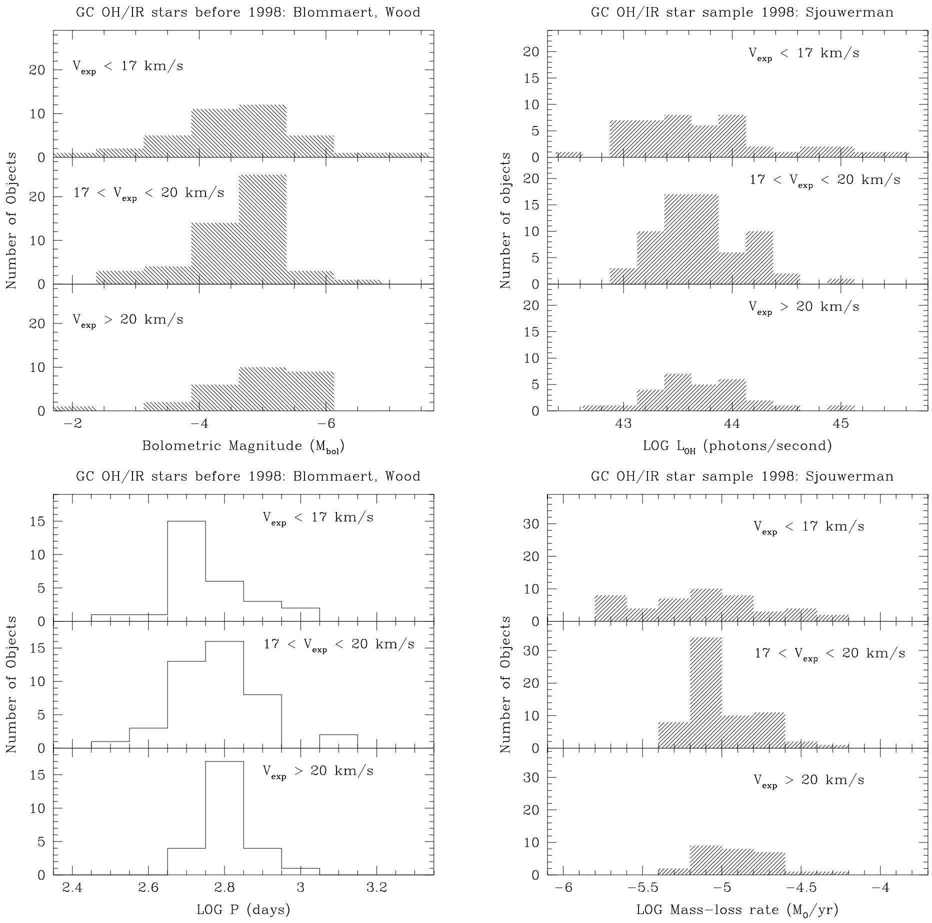

Figure 3. Physical properties of the central star ($M_{\rm bol}, P$) and the expanding OH masing shell ($\dot{\rm M}$, $L_{\rm OH}$) for each $v_{\rm exp}$-group. The latter properties are a function of δ (as well as L_*). See text.

We show histograms of several physical properties of the OH/IR stars in the GC in Fig. 3 (Blommaert et al., 1998, plus Wood et al., 1998, and Sjouwerman et al. 1998a; see also Jones et al. 1994 and van Langevelde et al. 1993). For $M_{\rm bol}$, $L_{\rm OH}$ and $\dot{\rm M}$, the peaked distributions in the group with $17 < v_{\rm exp} < 20$ km/s *cannot* be explained by the small range of 3 km/s in $v_{\rm exp}$; it is almost as wide as for the high $v_{\rm exp}$ group ($\sim$ 4 km/s). Also, it cannot be explained by a combination of stars with the wide distributions from the low and/or high $v_{\rm exp}$ groups, in particular when the dynamics of both groups are taken into account. That is, the velocity *and* sky distribution of the stars in this intermediate group resembles the velocity *and* sky distributions of the stars in the high $v_{\rm exp}$ group. Thus the intermediate $v_{\rm exp}$ group, which includes *all* the excess stars, may also contain a number of stars from the high $v_{\rm exp}$ group. Because both differ from the low $v_{\rm exp}$ group, it is unlikely that this intermediate $v_{\rm exp}$ group has a large contribution of stars from the low $v_{\rm exp}$ group.

We therefore *observe* that the peaked distributions for the group with $17 < v_{\rm exp} < 20$ km/s is caused by an excess of stars with almost *identical* physical properties, both in central star ($M_{\rm bol}$) as in circumstellar shell ($\dot{\rm M}$, $L_{\rm OH}$). That the period P does not seem to correlate with the $v_{\rm exp}$ group in our view confirms that the Mira P-$M_{\rm bol}$-relation breaks down for OH/IR stars (e.g. Feast et al. 1989, Blommaert et al. 1998, Wood et al. 1998). From Fig. 1, we see that the measured $M_{\rm bol}$ values and range per bin are roughly representative for each $v_{\rm exp}$-bin. For the excess stars we then derive $M_{\rm bol} \approx -4.5$ to -5 (also depending on extinction correction) combined with roughly identical metallicities (Eq. 1). Because the OH/IR stage is a very short lived phase in stellar evolution, these "excess" OH/IR stars all have the same main-sequence mass (M) and age (T), i.e. just as $M_{\rm bol}$ (L_*) and δ also in a very narrow range. In addition, the $17 < v_{\rm exp} < 20$ km/s group is rotating strongly and dynamically young (with a high age, see below). This all indicates that the excess OH/IR stars were formed in a short time. We conclude that this is evidence for an epoch of enhanced star formation in the GC.

4. Implications for a star formation epoch

Because the exact metallicity of the excess stars is not known, and due to a lack of high-metallicity models for OH/IR stars, we will use the models of Vassiliadis & Wood (1993) to illustrate the implications of our findings with some numbers in orders of magnitude. However, keep in mind that these models were constructed for luminous OH/IR stars in the LMC. We derive that for a star with $M_{\rm bol} \approx -5$ (or less), the main-sequence mass is 2 $M_\odot$ (or less), the metallicity of the originating molecular cloud ranges within $0.004 < Z < 0.008$, and the age T is $\gtrsim 1.1$ Gyr (or more). A much higher overall metallicity ($Z \gtrsim 0.03$), and thus a higher main-sequence mass for the excess OH/IR stars, is then inconsistent with the OH/IR star pulsation periods ($P \lesssim 1000^{\rm d}$, van Langevelde et al. 1993; Jones et al. 1994, Wood et al. 1998). This result is obviously one of the shortcomings of applying the models of Vassiliadis & Wood (1993) to the GC OH/IR stars.

Regardless of a precise knowledge of the metallicities, we can make a very simplified calculation of the total number of massive (OB) stars during the epoch of star formation outlined above. Although many factors are not well known, or might be different in a high metallicity environment as the GC, we will use as example the $Z = 0.008$ models of Vassiliadis & Wood (1993; see also e.g. Fagotto et al. 1994). We assume that an AGB star is observable as an OH/IR star only during the so-called 'superwind' phase on the AGB (9×10^4 yr for $M = 2$ $M_\odot$) and read in Table 2 of Vassiliadis & Wood (1993), that the total AGB phase lasts 1.5×10^7 yr. By comparing lifetimes of stars with small mass differences with the lifetime of the 'superwind' phase, we estimate an upper limit of the mass range for the OH/IR stars of 9×10^{-5} $M_\odot$ and infer that each OH/IR star represents 1.8×10^6 AGB stars in that mass range. Hence, because all OH/IR stars have the same mass and age, each OH/IR star observed can be converted to 1.8×10^6 stars with $M = 2$ $M_\odot$ during the formation of the stars. From our $v_{\rm exp}$ distribution, we estimate the minimum number N of OH/IR stars that is clearly in excess of what can be expected from the general mix of stars formed at other times, i.e. $N \gtrsim 20$. Without performing a detailed starburst calculation (see e.g.

Rieke et al. 1993), we estimate the total number of OB stars ($10 < M < 60$ $M_\odot$) to be roughly 10^6 (or a few 10^7 over $1 < M < 60$ $M_\odot$) during this event. To keep the metallicity of the cloud roughly constant, and the dynamics of the sample tight, the formation period must have been very short ($\ll 50$ Myr). The luminosity produced in the nucleus during this event ($\sim 10^{10} L_\odot$) is comparable to the luminosity of the Galaxy as a whole. Accordingly, the Galaxy would have been a starburst galaxy during this epoch of enhanced star formation.

Note that the calculations are very sensitive to the AGB star mass, mass range, as well as the adopted stellar models. However, by selecting the lowest estimates for the excess of OH/IR stars and the conversion into AGB stars (the zero point of the initial main-sequence mass function; IMF), we believe that this is a lower limit for the number of OB stars. Furthermore, the formation of low-mass stars is probably suppressed (e.g. Morris 1993). The low-mass cut-off in the IMF is probably a few $M_\odot$. If this cut-off for the GC is higher than the mass of the observed OH/IR stars, there is a relative deficit of observable OH/IR stars (thus underestimating N). Moreover, we have used a relatively steep power of -3 in the IMF, close to the value for the high-mass end of the IMF (e.g. Rieke et al. 1993). The intermediate-mass part of the IMF is likely to be less steep, resulting in a severe underestimate of the number of OB stars when starting the calculations from $M = 2$ $M_\odot$. When we continue, and estimate the mass of the molecular material from which our starburst resulted, we come to a cloud of a few times 10^8 $M_\odot$ (with a star formation efficiency of $\sim 20\%$; Genzel et al. 1995). We find our rough estimates consistent with the observations for starburst galaxies, for example the nearby starburst galaxies NGC 3504 and M 82 (Kenney et al. 1993; McLeod et al. 1993).

5. Conclusions

With a slightly different division in groups, we confirm the findings of Lindqvist et al. (1992b), Sevenster et al. (1995) and Serabyn & Morris (1996), i.e. one can statistically distinguish two groups of OH/IR stars with low and high $v_{\rm exp}$. The group with $v_{\rm exp} < 17$ km/s is in statistical sense "old" and is probably a bulge-like population. The group with $v_{\rm exp} \gtrsim 20$ km/s is statistically "young", and probably a result from sustained star formation. Furthermore, we have found a shrinking population of old stars (> 1 Gyr) with high (but unknown) metallicity (δ) and rapid rotation around the GC. These stars were formed in a short isolated era, for which the OH/IR stars with shell expansion velocities ($v_{\rm exp}$) between 17 and 20 km/s and $M \lesssim 2$ $M_\odot$ are currently the most massive representatives. At the time of formation, the Galaxy would have been classified as a starburst galaxy.

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