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LETTER

# SiO Maser Sources toward Globular Clusters

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**Abstract**

We report on the detection of SiO masers in Asymptotic Giant Branch variables toward bulge/disk globular clusters. In five out of six cases, the radial velocities are compatible with the optically measured radial velocities of globular clusters in the assessed uncertainty. Two sources, toward Terzan 5 and Terzan 12, lie very close to the cluster centers. The objects toward Pal 6 and Terzan 12 have luminosities appropriate to the AGB tip in globular clusters, while those toward NGC 6171, Pal 10, and Terzan 5 are brighter than expected. It is suggested that the latter three may have evolved from merged binaries, offering a test for binary-evolution scenarios in globular clusters, if the membership is approved.

**Key words:** circumstellar matter — globular clusters: general — radio lines: stars — stars: AGB and post-AGB

## 1. Introduction

Globular clusters (GCs, hereafter) are well-studied stellar systems containing the oldest stars in the Galaxy, and much of our knowledge of stellar dynamics and stellar evolution rests on them. With an age of about 10 Gyr, low-mass ($\sim 1\,M_\odot$) stars are now on the AGB phase in GCs. While younger, more massive, AGB stars often turn into infrared stars with thick dust shells due to heavy mass loss, the low-mass stars found in GCs do not appear to evolve in this manner. Although several red giants in GCs show small mid-infrared (MIR) excesses that indicate weak mass loss (Origlia et al. 2002; Ramdani, Jorissen 2001), they bear little resemblance to the dust-enshrouded stars found in young Magellanic clusters (Tanabé et al. 1997). Maser emission is another characteristic often seen in such objects (see Habing 1996). However, no maser sources have ever been found in GCs (Knapp, Kerr 1973; Bowers et al. 1979; Cohen, Malkan 1979; Dickey, Malkan 1980). A possible exception is the OH maser source V720 Oph in NGC 6171 (Frail, Beasley 1994). Feast and Whitelock (1994) suggested two possibilities for this object: to be a foreground star or to be an evolutionary product of a merged binary. Whereas previous surveys searched for OH and/or $H_2O$ masers, no SiO maser detection has yet been reported (for negative results with the VLA, see the Web page[1]). In this paper, we report on a result of SiO maser detections in AGB variables, possibly associated with GCs.

## 2. Observations and Results

Targets were selected from our program of near infrared (NIR) observations of more than 140 GCs taken from the known galactic total of 150. NIR monitoring observations started in 2002 March using an array camera (SIRIUS) attached to the 1.4 m IRSF telescope at the South African Astronomical Observatory [see Nagashima et al. (1999) and Nagayama et al. (2003) for instrumental details]. During the course of this work, we found several new red variables with $(J-K)_0 \geq 3.0$ mag. These stars are redder than the samples with small infrared excesses, studied by Origlia et al. (2002) or Ramdani and Jorissen (2001), at least in $(J-K)_0$, so they are more promising candidates for SiO maser emission.

For thirty two stars, the SiO maser lines ($J$ = 1–0, $v$ = 1 and 2) at 43.122 and 42.821 GHz (Lovas 1992), respectively, were searched for with the Nobeyama 45 m radio telescope during 2004 March 28–30 and on May 8. The half-power beam width was about 40″ at 43 GHz. We used a cooled SIS receiver ($T_{\rm sys} \sim$ 180–250 K) and acousto-optical spectrometers with high (40 kHz; AOS-H) and low (250 kHz; AOS-W) resolutions having 2048 channels each. The spectrometer arrays covered velocity ranges of $\pm 390\,{\rm km\,s^{-1}}$ and $\pm 800\,{\rm km\,s^{-1}}$ in AOS-H and AOS-W, respectively. The conversion factor of the antenna temperature to the flux density was $\sim 2.9\,{\rm Jy\,K^{-1}}$.

We detected SiO maser emissions from six red variables toward six GCs (among 32 surveyed stars), mostly in the direction of the galactic bulge. For the previously known variable stars in NGC 6171 and Pal 10, the variable IDs (V1 and V2, respectively) were taken from the catalog of variable stars in GCs by Clement et al. (2001). NGC 6171 V1 is V720 Oph, mentioned in section 1. The other four variables were newly found from our NIR observations, and named according to

[1] ⟨http://www.computing.edu.au/~bvk/astronomy/HET608/project/⟩.

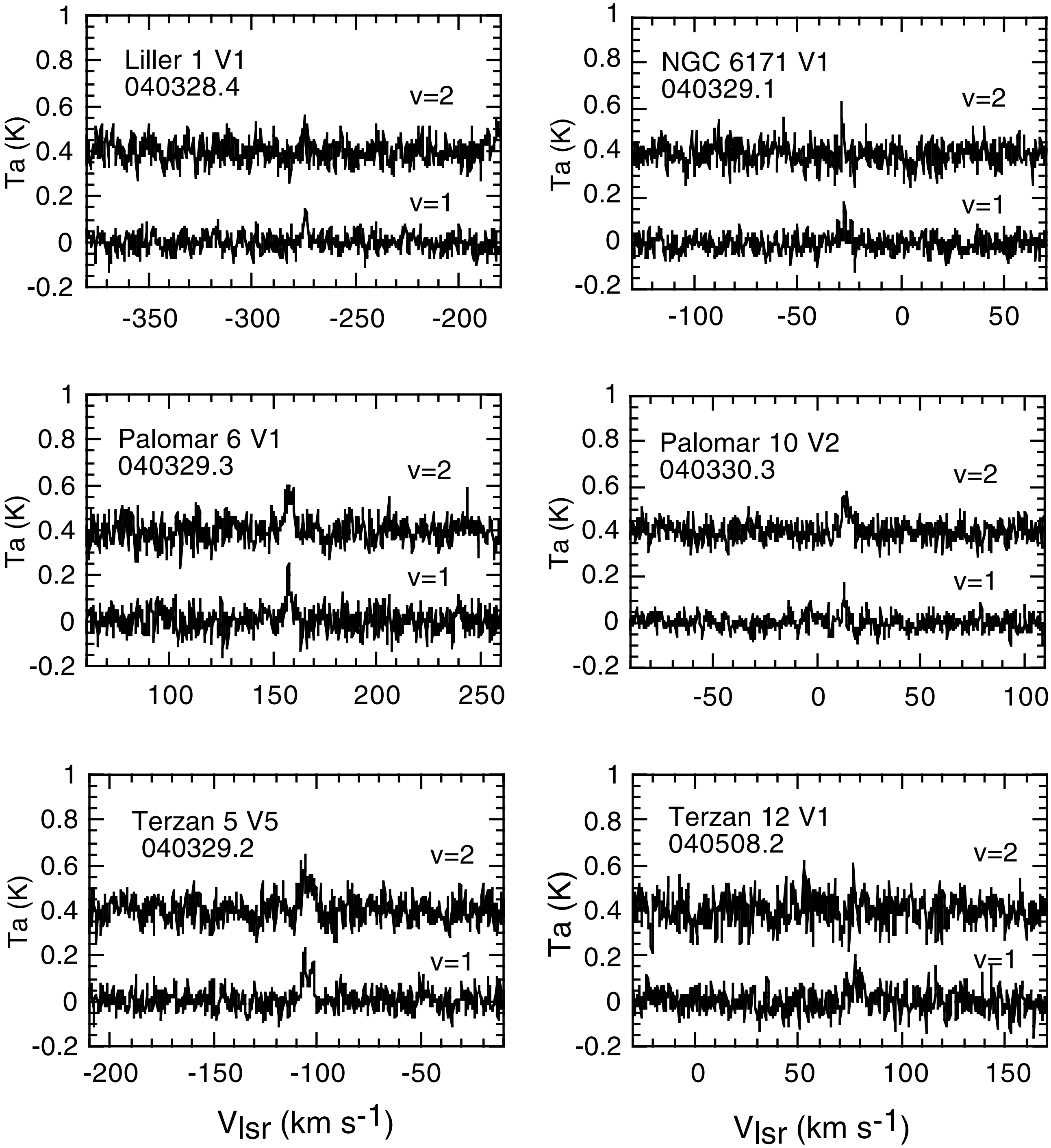


**Fig. 1.** Spectra of the SiO $J = 1$–0, $v = 2$ (top) and $v = 1$ line (bottom). The observation dates are listed in the format YYMMDD.D for all objects.

Clement's numbering system (namely Liller 1 V1, Pal 6 V1, Terzan 5 V5, and Terzan 12 V1). Lines of both $v = 1$ and $v = 2$ were detected, except in the case of Terzan 12 V1, for which only $v = 1$ was seen. Their spectra from AOS-H are shown in figure 1. The detection criteria used by Izumiura et al. (1999) were satisfied by these lines, except for marginal detections of the $v = 2$ lines in Liller 1 V1 and NGC 6171 V1. The integration time for each object was about 30 minutes, similar to those made in the past SiO surveys (Izumiura et al. 1999; Deguchi et al. 2000a,b). The detections were confirmed in AOS-W spectra in all cases. The observational properties of the detected objects are summarized in table 1, which contains the source positions, angular separations from the cluster center ($r_{\rm SiO}$), SiO transitions, radial velocities ($V_{\rm LSR}$), peak antenna temperatures ($T_{\rm a}$), integrated intensities, and rms noise levels for both transitions from the AOS-H spectra. Table 2 lists the properties of the GCs. They were mostly taken from a compilation by Harris (1996). In the table, $l$ and $b$ are the galactic

**Table 1.** SiO maser properties.

| Object | RA (J2000) | Dec (J2000) | $r_{SiO}$ | Transition | $V_{LSR}$ | Peak $T_a$ | Integ. int. | rms |
|---|---|---|---|---|---|---|---|---|
| | h m s | ° ′ ″ | (′) | $(J, v)$ | (km s$^{-1}$) | (K) | (K km s$^{-1}$) | (K) |
| Liller 1 V1 | 17 33 35.2 | −33 22 01.8 | 2.59 | 1–0, 1 | −275.1 | 0.143 | 0.337 | 0.039 |
| | | | | 1–0, 2 | −275.1 | 0.162 | 0.126 | 0.049 |
| NGC 6171 V1 | 16 32 24.6 | −13 12 01.3 | 8.98 | 1–0, 1 | −28.1 | 0.185 | 0.224 | 0.035 |
| | | | | 1–0, 2 | −28.8 | 0.230 | 0.201 | 0.048 |
| Pal 6 V1 | 17 43 49.5 | −26 15 27.9 | 2.67 | 1–0, 1 | 156.8 | 0.253 | 0.604 | 0.049 |
| | | | | 1–0, 2 | 157.2 | 0.229 | 0.739 | 0.045 |
| Pal 10 V2 | 19 17 51.5 | +18 34 12.6 | 2.51 | 1–0, 1 | 12.7 | 0.193 | 0.332 | 0.033 |
| | | | | 1–0, 2 | 14.7 | 0.173 | 0.653 | 0.041 |
| Terzan 5 V5 | 17 48 03.4 | −24 46 42.0 | 0.34 | 1–0, 1 | −106.8 | 0.232 | 0.778 | 0.043 |
| | | | | 1–0, 2 | −105.9 | 0.246 | 0.868 | 0.051 |
| Terzan 12 V1 | 18 12 14.2 | −22 43 58.8 | 0.64 | 1–0, 1 | 76.9 | 0.208 | 0.621 | 0.045 |
| | | | | 1–0, 2 | ··· | ··· | ··· | 0.065 |

**Table 2.** Cluster properties.

| Cluster | $l$ | $b$ | $V_{LSR}^{GC}(v_h)$ | $r_h$ | $r_t$ | DM | $E(B-V)$ | [Fe/H] | $N_{2M}(N_{MSX})$ | $P_{contm}^{<r_{SiO}}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | (°) | (°) | (km s$^{-1}$) | (′) | (′) | (mag) | (mag) | | | |
| Liller 1 | 354.84 | −0.16 | 61.0 (19.5) | 0.45 | 12.57 | 14.81 | 3.06 | 0.22 | 80(187) | 0.207 |
| NGC 6171 | 3.37 | 23.01 | −20.4 (17.2) | 2.70 | 17.44 | 14.02 | 0.33 | −1.04 | 1(5)$^{\dagger}$ | 0.034 |
| Pal 6 | 2.09 | 1.78 | 193.7*(20.9) | 1.06 | 8.36 | 13.82 | 1.46 | −1.09 | 52(96) | 0.148 |
| Pal 10 | 52.44 | 2.72 | −13.3*(13.6) | 0.99 | 3.08 | 13.79 | 1.66 | −0.10 | 5(19) | 0.014 |
| Terzan 5 | 3.84 | 1.69 | −82.4 (32.2) | 0.83 | 13.27 | 14.97 | 2.15 | 0.00 | 64(70) | 0.003 |
| Terzan 12 | 8.36 | −2.10 | 106.3* (7.8) | 0.84 | 3.10 | 13.33 | 2.06 | −0.50 | 34(64) | 0.006 |

* The value is assessed to be uncertain more than 10 km s$^{-1}$ (see subsection 3.1).
† Evaluated from IRAS PSC and 2MASS with $K < 10$ and $H - K > 0.6$ (MSX not available at this $b$).

coordinates of the cluster center, $V_{LSR}^{GC}$ is the cluster velocity with respect to the Local Standard of Rest (with the escape velocity $v_h$ at half radius between parentheses),[2] $r_h$ and $r_t$ are the half-mass radius and the tidal radius of the cluster respectively, and [Fe/H] is the metallicity. In addition, we give DM (the distance modulus of each clusters) and $E(B-V)$ (the reddening) used to calculate the absolute bolometric magnitudes in subsection 3.3, and $N_{2M}$ and $P_{contm}^{<r_{SiO}}$, the number of NIR SiO candidates within 34′ of the cluster and the contamination probability, which are discussed in subsection 3.2.

## 3. Discussions

### *3.1. Position and Velocity*

All six sources are located well within the projected tidal radii, $r_t$ of the GCs. Terzan 5 V5 and Terzan 12 V1 lie within the half-mass radii, $r_h$, i.e., very close to the cluster centers within 1′.

Because the radial velocity of SiO maser emission is known to coincide with that of the central star within a few km s$^{-1}$ (Jewell et al. 1991), it can be compared directly with the velocity of the cluster. Except for Liller 1 V1, the SiO radial velocities fall near to the optically measured velocities of GCs with velocity separations of 8–37 km s$^{-1}$. The velocity dispersion within a GC depends on its mass; about 10 km s$^{-1}$ for the most massive clusters, and only a few km s$^{-1}$ for small ones (see table 2 of Mandushev et al. 1991). Gnedin et al. (2002) calculated the escape velocities (as well as the velocity dispersions) at half radii and the cluster centers of 147 GCs, using isotropic King models with a constant mass–luminosity ratio ($M/L_V = 3$); these escape velocities at the half radii are listed between the parentheses in the 4th column of table 2. For NGC 6171 V1 and Terzan 5 V5, the observed velocity differences of the SiO masers to the GCs are well within the escape velocities of the globular clusters, though they are slightly above the one-dimensional velocity dispersions given in the Gnedin's table. For Pal 6 V1 and Pal 10 V2, the velocity differences are a factor of about 1.8 larger than the escape velocity, and for Terzan 12 V1, a factor of 4.2 larger. However, note that the accuracy of the radial-velocity measurements is quite poor for these three clusters. They were obtained from the average of the radial velocities of a few giants, which were selected from a sample of a handful of stars, excluding objects with a large velocity separation; historic examples in velocity measurements of GCs suggest a typical uncertainty of about ±20 km s$^{-1}$ (see table 3 of Coelho et al. 2001). For Pal 6,

[2] Taken from the table of escape velocities used for Gnedin et al. (2002), which is available at ⟨http://www-astronomy.mps.ohio-state.edu/~ognedin/gc/⟩.

the velocity was derived from only two (table 3 of Minniti et al. 1995) or four giants (Lee et al. 2004); their values differ by about 20 km $s^{-1}$. For Pal 10 and Terzan 12, the radial velocities of only two stars were used (Côté 1999).

With this caveat, the velocities of the SiO masers are considered not to be incompatible with those of the clusters, except in the case of Liller 1 V1, whose membership is rejected. Better optical velocity measurements of the surrounding giants would be necessary to establish the memberships of the SiO masers from the velocity coincidence with greater certainty. On the other hand, the radial velocity of NGC 6171 has been studied based on the spectra of a number of giants (Da Costa, Seitzer 1989; Suntzeff et al. 1993; Piatek et al. 1994). Harris (1996) gives a velocity of $-20.4$ km $s^{-1}$, obtained by combining their results. This is in reasonable agreement with the SiO maser velocity ($-28.4$ km $s^{-1}$), despite the large angular separation ($\sim 9'$) from the cluster center. There have also been proper-motion studies concerning this cluster, which support the membership (Frail, Beasley 1994). Also, for Terzan 5, the radial velocity, which was recently derived using 4 stars (Origlia, Rich 2004), coincides with the previous value listed by Harris (1996), as well as with the SiO maser velocity within a tolerable range. Thus, NGC 6171 V1 and Terzan 5 V5 cannot be rejected as being members of the clusters from a kinematic point of view.

### 3.2. *Concentration of Detections to the Galactic Bulge*

Among the six GCs, five are located in the galactic bulge, the exception being Pal 10, which is in the galactic disk. Because of the high density of AGB stars in these areas, possible contamination by the bulge AGB stars with SiO masers in the line of sight must be examined. The surface number density of SiO maser sources is estimated to be approximately 10–20 sources per square degree in the galactic bulge; this number was obtained by averaging the numbers found in the inner bulge in past surveys covering an area of $25^\circ \times 6^\circ$ (Deguchi et al. 2000a,b), corrected (with multiplying by a factor of ten) for limited color ranges [$0 < \log(F_{25}/F_{12}) < 0.1$] and flux density limits ($F_{12} > 2$ Jy) of the above-noted observations. This gives 0.16 at most for the number of spurious SiO sources falling within $3'$ from the center of a cluster in the bulge. Furthermore, a probability of contamination by the disk/bulge objects was evaluated for individual directions of GCs by counting MSX sources with 12 $\mu$m flux density above 1 Jy having a NIR counterpart falling within $5''$ with $K < 10$ and $H - K > 0.8$ in the 2MASS catalog; these are potential candidate SiO maser sources, and from past experience, half of these objects exhibit SiO masers. The results are shown in the last two columns of table 2, listing the number of NIR counterparts satisfying the above conditions within $34'$ (1 square degree) of the GC (between parentheses, the number of MSX sources above 1 Jy in the same area), and the probability of contamination, finding more than one such object within $r_{\mathrm{SiO}}$ toward the globular cluster with a SiO detection rate of 50%. These numbers are quite consistent with the value obtained from the above estimate based on the known SiO maser sources in the bulge.

In addition, the radial velocities of the bulge SiO maser sources spread over approximately $\pm 200$ km $s^{-1}$. The chance of an accidental coincidence of a bulge SiO source both in position and velocity is thus considered to be quite small unless the motions of the bulge GCs are dominated by bulge-bar star kinematics, though this is somewhat dubious; e.g., Côté (1999). While that in Liller 1 is probably in fact an accidental coincidence, it is highly unlikely that all of our detections were by chance.

It is also interesting to note that the present detections of SiO masers are limited to the bulge/disk GCs. As mentioned in section 1, a previous massive SiO maser search with the VLA failed to find SiO maser emission in any halo GCs. Furthermore, mass-losing AGB candidates, i.e., the very red stars found in our NIR observations and/or those identified in the MSX/IRAS surveys, are only found in bulge clusters. These facts indicate that the bulge GCs have AGB stellar populations that differ in their characteristics from those in the halo. A possible explanation is that the bulge GCs are relatively metal-rich ($\sim 1/10$ to 1 solar abundance; see table 2). The molecular abundances, especially for SiO, are enhanced in a metal-rich environment.

### 3.3. *Bolometric Magnitude*

Because the peaks of the spectral energy distribution of mass-losing AGB stars, such as those discussed here, lie in the region of the NIR and MIR, their bolometric magnitudes can be estimated by combining our NIR photometric data with MIR catalogs, such as IRAS and MSX (Egan et al. 2003). For the newly discovered variables, we adopted mean magnitudes from our NIR light curves. They all show large amplitudes that are typical for mass-losing stars. For the other two variables that are too bright for us to monitor, we adopted their magnitudes from the 2MASS All Sky Data Release (Cutri et al. 2003). Comparing the magnitude of NGC 6171 V1 with that reported by Feast and Whitelock (1994), it is probably not far from its mean magnitude. The adopted magnitudes are listed in table 3, which also indicates the corresponding MSX source and/or IRAS point source, if any. The bolometric magnitudes, $m_{\mathrm{bol}}$ were calculated by integrating under trapezoidal lines drawn in $\log \nu$–$\nu F_\nu$ diagrams. While we ignored the contributions from shorter wavelengths, we applied Rayleigh–Jeans curves for the longer ones. The uncertainties are expected to be about 0.2 mag, mainly arising from the uncertainties of the mean-magnitude determinations in the NIR and the flux density errors in the MIR. In table 3 the results are also listed along with the derived absolute bolometric magnitudes obtained by correcting for the assumed cluster distance moduli and reddening values.

The derived $M_{\mathrm{bol}}$ values should be lower than those of the AGB tips, which depend on the age and chemical composition. Aaronson and Mould (1985) showed that the younger AGB stars evolve upwards in luminosity. They consider that the tip luminosity for metal-rich GCs is about $-4.5$ mag at an age of about 10 Gyr. Only Pal 6 V1 and Terzan 12 have a $M_{\mathrm{bol}}$ value consistent with this limit, i.e., lower than $-4.5$. On the other hand, the merger of binary systems or direct collision can produce massive objects that would reach higher luminosity (Bailyn 1995). This possibility is also mentioned by Feast and Whitelock (1994). This is related to a problem concerning planetary nebulae (PNe) in GCs. So far, four PNe are known to

**Table 3.** Photometric properties of SiO maser sources.

| Object | $J$ | $H$ | $K_s$ | MSX6C | IRAS PSC | $m_{bol}$ | Derived $M_{bol}$ |
|---|---|---|---|---|---|---|---|
| Liller 1 V1 | 14.70 | 11.80 | 9.00 | G354.8792−00.1798 | ··· | 11.0 | −3.8 |
| NGC 6171 V1 | 6.02 | 5.16 | 4.54 | ··· | 16296−1305 | 7.4 | −6.6 |
| Pal 6 V1 | ··· | 12.00 | 9.00 | G002.0765+01.7380 | 17406−2614 | 10.4 | −3.5 |
| Pal 10 V2 | 6.79 | 5.58 | 4.87 | G052.4153+02.7613 | 19156+1828 | 7.4 | −6.4 |
| Terzan 5 V5 | 9.90 | 8.20 | 6.90 | G003.8381+01.6895 | ··· | 9.3 | −5.6 |
| Terzan 12 V1 | 9.30 | 7.70 | 6.50 | G008.3630−02.0909 | 18092−2244 | 9.0 | −4.3 |

exist in GCs (Ps-1 in M 15, Pease 1928; GJJC-1 in M 22, Gillett et al. 1989; JaFu-1 in Pal 6 and JaFu-2 in NGC 6441, Jacoby et al. 1997). While this number is less than expected based on the assumption that every dying star produces a PN, current models predict that the masses of white dwarfs in GCs are too small to produce PNe (see Jacoby et al. 1997; Alves et al. 2000, and references therein). These authors suggested that only special objects, whose masses are augmented in close-binary interaction, can become PNe. Because the variable stars with heavy mass-loss have a lifetime roughly equal to that of planetary nebulae, it seems natural to expect the same number of them, both of which are considered to be products of merged binaries. Since blue stragglers are common in GCs (Piotto et al. 2004) and also with the recent discoveries that they contain numerous low-mass X-ray binaries and millisecond pulsars (Lyne et al. 2000), it is strongly suggested that close-binary formations and merger events occur relatively often in them (Pooley et al. 2003). With these indications and our new detection of masers with high luminosities (NGC 6171 V1, Pal 10 V2, and Terzan 5 V5), we support the idea of a merged binary by Feast and Whitelock (1994). It may be slightly premature, however, at this stage to discuss their statistics and formation rates before further complete surveys are made.

## 4. Conclusion

Among the six SiO maser sources that we detected in the present survey, five, with the exception of Liller 1 V1, stand as potential candidates for GC members. Among them, the variables toward NGC 6171 and Terzan 5 are highly likely GC members, though those toward Pal 6, Pal 10, and Terzan 12, are somewhat debatable. The membership must be approved (or disproved) much more firmly in future observations, because some uncertainty remains as to the coincidence of the maser velocities with those of the clusters due to a lack of precision in the optical velocity measurements of GCs. These maser sources are dust-enshrouded AGB stars that were not expected in GCs in the past. Some of them have luminosities that are too high to fit the standard evolutionary tracks of low-mass stars, and may have evolved from binary mergers. On the other hand, SiO sources toward Pal 6 and Terzan 12 have luminosities that are consistent with the normal stellar evolution of old stars, though they might also be special objects at a certain stage of close-binary interaction.

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## References

Aaronson, M., & Mould, J. 1985, ApJ, 288, 551
Alves, D. R., Bond, H. E., & Livio, M. 2000, AJ, 120, 2044
Bailyn, C. D. 1995, ARA&A, 33, 133
Bowers, P. F., Kerr, F. J., Knapp, G. R., Gallagher, J. S., & Hunter, D. A. 1979, ApJ, 233, 553
Clement, C. M., et al. 2001, AJ, 122, 2587
Coelho, P., Barbuy, B., Perrin, M.-N., Idiart, T., Schiavon, R. P., Ortolani, S., & Bica, E. 2001, A&A, 376, 136
Cohen, N. L., & Malkan, M. A. 1979, AJ, 84, 74
Côté, P. 1999, AJ, 118, 406
Cutri, R. M., et al. 2003, Explanatory Supplement to the 2MASS All Sky Data Release (Pasadena: Caltech)
Da Costa, G. S., & Seitzer, P. 1989, AJ, 97, 405
Deguchi, S., Fujii, T., Izumiura, H., Kameya, O., Nakada, Y., & Nakashima, J. 2000a, ApJS, 130, 351
Deguchi, S., Fujii, T., Izumiura, H., Kameya, O., Nakada, Y., Nakashima, J., Ootsubo, T., & Ukita, N. 2000b, ApJS, 128, 571
Dickey, J. M., & Malkan, M. A. 1980, AJ, 85, 145
Egan, M. P., et al., 2003, The Midcourse Space Experiment Point Source Catalog Version 2.3, Air Force Research Laboratory Technical Report (AFRL-VS-TR-2003-1589)
Feast, M. W., & Whitelock, P. A. 1994, A&A, 287, L29
Frail, D. A., & Beasley, A. J. 1994, A&A, 290, 796
Gillett, F. C., Jacoby, G. H., Joyce, R. R., Cohen, J. G., Neugebauer, G., Soifer, B. T., Nakajima, T., & Matthews, K. 1989, ApJ, 338, 862
Gnedin, O. Y., Zhao, H. S., Pringle, J. E., Fall, S. M., Livio, M., & Meylan, G. 2002, ApJ, 568, L23
Habing, H. J. 1996, A&AR, 7, 97
Harris, W. E. 1996, AJ, 112, 1487

Izumiura, H., Deguchi, S., Fujii, T., Kameya, O., Matsumoto, S., Nakada, Y., Ootsubo, T., & Ukita, N. 1999, ApJS, 125, 257

Jacoby, G. H., Morse, J. A., Fullton, L. K., Kwitter, K. B., & Henry, R. B. C. 1997, AJ, 114, 2611

Jewell, P. R., Snyder, L. E., Walmsley, C. M., Wilson, T. L., & Gensheimer, P. D. 1991, A&A, 242, 211

Knapp, G. R., & Kerr, F. J. 1973, AJ, 78, 458

Lee, J.-W., Carney, B. W., & Balachandran, S. C. 2004, AJ, 128, 2388

Lovas, F. J. 1992, J. Phys. Chem. Ref. Data, 21, 181

Lyne, A. G., Mankelow, S. H., Bell, J. F., & Manchester, R. N. 2000, MNRAS, 316, 491

Mandushev, G., Spassova, N., & Staneva, A. 1991, A&A, 252, 94

Minniti, D. 1995, A&A, 303, 468

Nagashima, C., et al. 1999, in Proc. Star Formation 1999, Star Formation, ed. T. Nakamoto (Nagoya: Nagoya University), 397

Nagayama, T., et al. 2003, in Proc. SPIE 4841, Instrument Design and Performance for Optical/Infrared Ground-based Telescopes, ed. M. Iye & A. F. M. Moorwood, 459

Origlia, L., Ferraro, F. R., Fusi Pecci, F., & Rood, R. T. 2002, ApJ, 571, 458

Origlia, L., & Rich, R. M. 2004, AJ, 127, 3422

Pease, F. G. 1928, PASP, 40, 342

Piatek, S., Pryor, C., McClure, R. D., Fletcher, J. M., & Hesser, J. E. 1994, AJ, 107, 1397

Piotto, G., et al. 2004, ApJ, 604, L109

Pooley, D., et al. 2003, ApJ, 591, L131

Ramdani, A., & Jorissen, A. 2001, A&A, 372, 85

Suntzeff, N. B., Mateo, M., Terndrup, D. M., Olszewski, E. W., Geisler, D., & Weller, W. 1993, ApJ, 418, 208

Tanabé, T., et al. 1997, Nature, 385, 509