The Astrophysical Journal, 647:L139–L142, 2006 August 20

SiO MASERS IN A SCUTUM MASSIVE STAR CLUSTER OF RED SUPERGIANTS

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Received 2006 April 20; accepted 2006 July 6; published 2006 August 7

ABSTRACT

We have detected five objects toward a Scutum massive star cluster of red supergiants in the SiO $J = 1–0$, $v = 1$ or $v = 2$ transitions. The radial velocity data indicate that four of the detections are cluster members and that the other, which is located close to the X-ray source AX 1838−0655, is a foreground object. The high velocity resolution of the maser lines provides a more accurate determination of the radial velocity (120 km s^{-1}) and velocity dispersion (~2 km s^{-1}) of the cluster and, hence, of the distance (6.5 kpc) and luminosities of the stars. We discuss the implications of these measurements in constraining the relationships between SiO masers and mass-loss rate and modeling the cluster age and mass.

Subject headings: masers — open clusters and associations: individual ([BDS2003] 122) — supergiants

1. INTRODUCTION

Recent infrared surveys have revealed a large number of previously unknown, young stellar clusters embedded in the Galactic disk (Dutra & Bica 2000; Lada & Lada 2003; Mercer et al. 2005). These star clusters provide excellent tests of stellar evolution and Galactic dynamics thanks to their coeval ages and the similar histories of their members. One such cluster in Scutum (No. 122 in the catalog of Bica et al. 2003) is remarkable for containing 14 red supergiants (Figer et al. 2006). These stars were identified as M supergiants by the large equivalent widths of the first CO overtone at 2.3 μm. No other single cluster contains more than five (spectroscopically confirmed) red supergiants. Combined with a high *K*-band luminosity, this distinguishes red supergiants from lower mass asymptotic giant branch (AGB) stars (Schultheis et al. 2003). Red supergiants have an even more severe mass-loss rate than AGB stars and are often enshrouded in a thick dust envelope. Red supergiants frequently support strong OH, H_2O, and SiO masers. Such stars can, however, arise from progenitors with a wide range of masses ($\gtrsim 10\ M_\odot$), and the age, evolutionary rate, and eventual fate of field red supergiants are often unclear. The ages and masses of the stars in the Scutum massive cluster have been estimated to be between 8 and 13 Myr and about 10 $M_\odot$, respectively (Figer et al. 2006). Known masses and ages of the red supergiants in the Scutum cluster may provide a clue to disentangling the complexity due to multiple-star mass transfer or mergers during the stellar evolution of supergiants (as in V838 Mon; see Deguchi et al. 2005).

In this Letter, we report the results of observations of the red supergiants in the Scutum star cluster in the 43 GHz SiO and 22 GHz H_2O maser lines. The maser line observations provide accurate radial velocities for these stars. From these data, we can obtain the kinematic distance of the cluster and infer the ratio of kinetic to gravitational energy, which determines a disruption speed for this open cluster.

2. OBSERVATIONS AND RESULTS

Simultaneous observations in the SiO $J = 1–0$, $v = 1$ and $v = 2$ transitions, at 43.122 and 42.821 GHz, respectively, were made with the 45 m radio telescope at Nobeyama on 2006 February 16–19. We used a cooled HEMT receiver ("H40") for the 43 GHz observations, and acousto-optical spectrometer arrays having an effective velocity resolution of 0.3 km s^{-1}. The system temperature was about 200 K. The conversion factor from antenna temperature to flux density was about 2.9 Jy K^{-1}. The half-power beamwidth (HPBW) was about 40″. The beam shape of the telescope is nicely Gaussian; pointing errors due to wind (typically 5″–10″ in the case of wind velocities over 5 m s^{-1}) cause a complication in source identifications for crowded regions, as in the present case. We observed a strong maser source, IRC +00363, before and after the observing sequences and confirmed that the pointing errors were less than 10″ with respect to its position from the Two Micron All Sky Survey (2MASS) (see Deguchi et al. [2002] for further details on the beam and pointing accuracy of the Nobeyama 45 m telescope). We employed an efficient position-switching sequence that allowed us to observe three objects consecutively between each blank field. In addition to the SiO maser observations, we made a 22.235 GHz H_2O maser observation on February 15, when weather was unfavorable for 43 GHz observations. We used a cooled HEMT receiver ("H22") and the same acousto-optical spectrometer arrays (with effective velocity resolution of 0.6 km s^{-1}). The conversion factor from antenna temperature to flux density was about 2.8 Jy K^{-1} at 22 GHz. Further details of observing with the Nobeyama 45 m telescope are presented elsewhere (e.g., Nakashima & Deguchi 2003a).

Our observational results are summarized in Table 1. We observed all the M supergiants, F01–F14, identified by Figer et al. (2006); we use their object numbers prefixed by "F." We also observed F15, a G6 I star, and F16 and F17, which do not have published spectra. We also observed another object, X18 (=J18380162−0655235, or MSX6C G025.2454−00.1885), 2′ south of this cluster, of similar IR brightness ($K = 6.88$), as Malizia et al. (2005) suspected that it was associated with the X-ray–to–TeV γ-ray source AX 18318−0655.

Because the red supergiants are tightly clustered (see Fig. 1), we used the line intensities, peak radial velocities, and line profiles (including the intensity ratio between the two SiO transitions) to assign the lines detected to the correct stars. We found similar line profiles for stars F01 and F02 (separation

TABLE 1
Observational Results by SiO Maser Line

		J = 1–0, v = 1				J = 1–0, v = 2			
ID	2MASS Name	T_a (K)	V_{lsr} (km s^{-1})	Integ. Intens. (K km s^{-1})	rms (K)	T_a (K)	V_{lsr} (km s^{-1})	Integ. Intens. (K km s^{-1})	rms (K)
F01	J18375629−0652322	0.316	115.0	2.110	0.076	...	...	...	0.074
F02	J18375528−0652484	0.394	120.0	2.518	0.070	...	...	...	0.070
F03	J18375973−0653494	...	...	...	0.058	...	...	...	0.059
F04	J18375090−0653382	0.336	121.5	1.387	0.057	...	...	...	0.061
F05	J18375550−0652122		(0.260, 117.5, 1.230)[a]		0.057	...	...	...	0.062
F06	J18375745−0653253	...	...	...	0.055	...	...	...	0.058
F07	J18375430−0652347		(0.299, 120.0, 1.769)[a]		0.068	...	...	...	0.070
F09	J18375777−0652222		(0.379, 116.5, 2.399)[b]		0.060		(0.326, 116.5, 0.950)[b]		0.059
F10	J18375952−0653319	...	...	...	0.057	...	...	...	0.059
F11	J18375172−0651499	...	...	...	0.071	...	...	...	0.070
F12	J18380330−0652451	...	...	...	0.069	...	...	...	0.069
F13	J18375890−0652321	0.493	116.5	3.242	0.061	0.486	116.4	2.082	0.056
F14	J18374764−0653023	...	...	...	0.058	...	...	...	0.058
F16	J18380129−0652519	...	...	...	0.062	...	...	...	0.061
X18	J18380162−0655235	0.554	74.3	3.405	0.078	0.771	74.3	3.765	0.080

[a] This is likely a contamination from F01 and F02.
[b] This is likely a contamination from F13.

22″) and for stars F09 and F13 (separation 19″), so we reobserved these objects on a day without wind. We found that F01 and F02 had similar intensities in the $v = 1$ transition, with no $v = 2$ emission, so we concluded that they were separate SiO sources.[1] F05 and F07 were also detected in $v = 1$ only, at about half the intensity of F01 and F02, consistent with emission contaminated by the Gaussian tails of the F01 and F02 masers. The intensities of both the $v = 1$ and $v = 2$ transitions at the position of F09 were about half the intensities at the position of F13, so we concluded that the latter was responsible for all the SiO emission detected at both positions. We could not resolve F05 and F08 (separation 4″).

In summary, we detected SiO maser emission from five objects: stars F01, F02, F04, F13, and X18. The line profiles of these sources are given in Figure 2. The radial velocity of object X18, at 74.3 km s^{-1}, is much lower than the average velocity of the stars in the M supergiant cluster, indicating that this is not a member of the cluster. The average velocity and standard deviation for the four cluster members (F01, F02, F04, and F13) are 118.1 and 2.8 km s^{-1}, respectively.

Water maser emission was detected in a pointing toward the star F09 (Fig. 2, *bottom right*). Similar but weak H_2O emission

[1] In addition, we detected the SiO J = 2–1, v = 1 maser line at 86.243 GHz at the pair of positions F01 and F02 with nearly equal intensities with the same telescope (HPBW = 19″) on 2006 April 14. This assures us that both stars F01 and F02 are SiO maser sources.

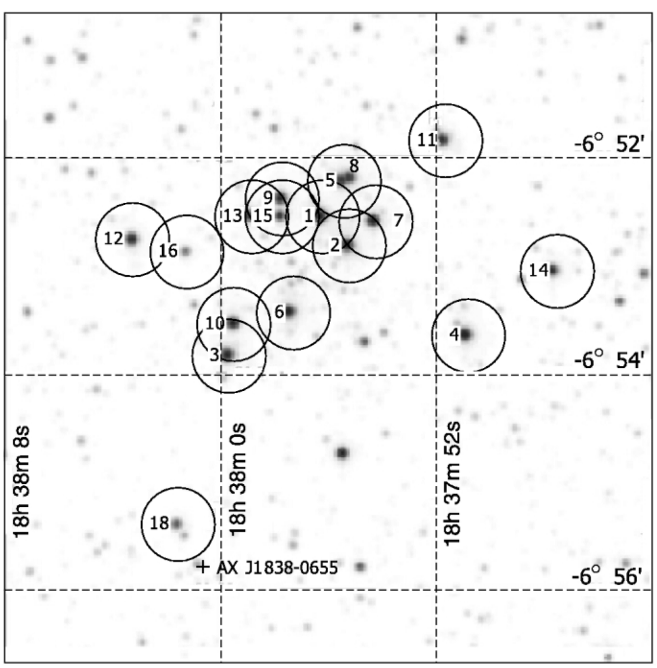

Fig. 1.—Observed positions and telescope beam areas (HPBW = 40″) overlaid on the 2MASS image toward the Scutum star cluster (6′ × 6′). The numbers 1–16 indicate the objects F01–F16, and 18 is for X18.

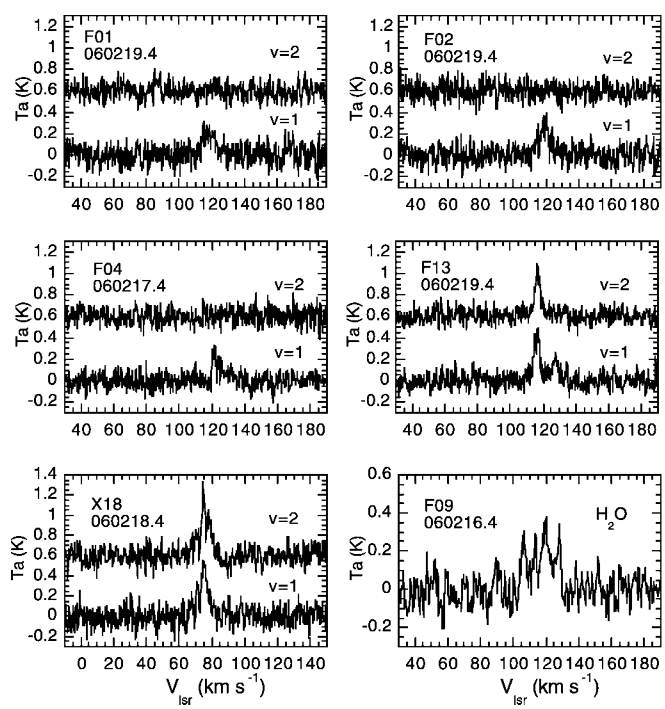

Fig. 2.—Spectra of the SiO J = 1–0, v = 1 and v = 2 transitions, except for the bottom right panel, which shows the H_2O 6_{16}–5_{23} transition. The object ID and date of observation (in *yymmdd.d* format) are shown at upper left in each panel. The H_2O maser emission detected in the pointing toward F09 is likely to have come from object F13 (see text).

was detected at positions F05 and F06 but not detected at positions F03, F04, and F10. Because of the large beam in the 22 GHz H_2O observations (HPBW = 73″), the emission could possibly be coming from star F01, F02, F05, F07, F08, F09, or F13. The large width of the H_2O emission is most similar to the broad line width in the SiO $J = 1$–0, $v = 1$ emission from star F13, suggesting that both masers are associated with F13. Furthermore, the H_2O maser profile has several peaks between 105 and 130 km s^{-1}, suggesting that this water maser source is associated with OH 25.284−0.156. This OH 1612 MHz source has a single peak at $V_{lsr} = 102.2$ km s^{-1} (Blommaert et al. 1994), which is likely to be a blueshifted component of a typical expanding OH shell. The VLA position of this OH source falls a few arcseconds east of the midpoint of positions of F09 and F15, but it also overlaps the positional uncertainty of F13 (Figer et al. 2006).

3. DISCUSSION

3.1. *Radial Velocity and Kinematic Distance of the Scutum Cluster*

It is well known that the radial velocity of SiO masers from evolved stars approximates the stellar systemic velocity (Jewell et al. 1991); SiO emission falls between the velocities of OH 1612 MHz double peaks that originate from the front and rear parts of an expanding shell, or at the center of broad CO emission, with the exception of a few objects with wide-separation double-peaked SiO spectra. The average radial velocity difference between the stellar velocity (CO and OH) and the SiO $v = 1$ maser velocity is only ∼0.3 km s^{-1} in the sample of Cho et al. (1996). The deviation in a single-epoch measurement for red supergiants could be larger.[2] Deguchi et al. (2004) gave the velocity difference and the standard error, 0.47 ± 1.88 km s^{-1}, for 49 sources in the Galactic center using only OH 1612 MHz data. The standard deviation of the difference between the SiO velocity and the stellar velocity is approximately 2 km s^{-1}.

With this fact in mind, we can evaluate the radial velocity of the cluster from the average velocity of the four SiO-detected cluster members, which is 118.1 km s^{-1} with a standard deviation of 2.8 km s^{-1}. The radial velocity derived from the peak intensity may be sensitive to the noise level in the observed profile and also to the time variability of the various maser features within a profile. Therefore, we also measured the radial velocity of each source using a second method, by taking the averages of the high- and low-velocity edges of each detected profile. The average radial velocities for stars F01, F02, F04, and F13 estimated using this method are 117.7, 119.7, 124.3, and 120.5 km s^{-1}, respectively, giving an average of 120.7 km s^{-1} with a standard deviation of 3.2 km s^{-1}.

Thus, the radial velocity of the cluster is about 120 km s^{-1}. If we use the V_{lsr}-distance curve given in Figure 10 of Figer et al. (2006), the kinematic distance of the cluster is 6.5 kpc (though it goes up to the distance of the tangential point [7.2 kpc], depending on the assumed rotation curve). This is an improvement on the result of Figer et al., because their estimate of the kinematic distance to this cluster of 5.8 kpc was based on the singly peaked OH radial velocity of 102 km s^{-1}. The correction in the distance requires a bolometric magnitude correction of $\Delta M_{bol} = 0.25$, which does not produce large changes in previous estimates of the stellar parameters in the Scutum cluster.

The distance of 6.5 kpc places this cluster beyond the tip of the bulge bar, the major axis of which makes an angle of approximately 20°–30° to the Sun–Galactic center line (Nikolaev & Weinberg 1997; see the face-on view of the Galactic plane, Fig. 5 of Russeil [2003], in which the locations of the bar and spiral arms are comprehensively plotted). The Scutum cluster ($l = 25\overset{\circ}{.}3$) is certainly not associated with the 3 kpc arm, which is traced approximately below $(l, V_{lsr}) = (10°, 0$ km $s^{-1})$ (Lockman 1980). The location of the Scutum cluster falls near the starting point of the Norma arm, where H II regions extending from both the Norma and Scutum-Crux arms are seen. The distance of the cluster from the Galactic Center is approximately 3.5 kpc, indicating that it is close to the corotation radius (∼3.4 ± 0.3 kpc) of the bulge bar (Bissantz et al. 2003). It has been proposed that various resonance activities such as the 3 kpc arm occur inside the corotation radius (Yuan & Chi 1991). The position of the Scutum cluster is also close to the Lagrangian point of the rotating bar potential, where tidal disruption of the cluster is marginal (see Fig. 5 [*right*] of Englmaier & Gerhard 1999). This may be the reason for the formation of a supermassive star cluster at this position in the Galaxy.

3.2. *Velocity Dispersion of Red Supergiants in the Scutum Cluster*

The velocity dispersion of stars in a cluster is one of the important physical quantities needed to infer the disruption speed of the cluster (Lyngå & Palouš 1987). Because we have the radial velocities of only four cluster members at present, we have to carefully discuss the stellar velocity dispersion of the red supergiant cluster.

We adopt a value of 2 km s^{-1} for the random deviation inherent to intrinsic SiO velocity measurements (Deguchi et al. 2004). The observed standard deviation of maser velocities is the resultant of this random deviation and the actual stellar velocity dispersion. We found standard deviations of 2.8 and 3.2 km s^{-1} in the SiO maser peak and profile center velocities, respectively. We deduce that the radial velocity dispersion of the red supergiants in the Scutum cluster is 2.0–2.5 km s^{-1}. Note that the uncertainty is due to the small numbers in the sample, as well as the possible offset between the SiO and stellar velocities.

Given the velocity dispersion of 2.0 km s^{-1}, the virial mass ($\equiv 6\overline{r}\overline{v_r^2}/G$; Eigenbrod et al. 2004) is $1.1 \times 10^4\ M_{\odot}$, assuming $\overline{r} = 2$ pc. Here $\overline{r}$ and $\overline{v_r^2}$ are the average radius and the radial velocity dispersion of the cluster, and G is the gravitational constant. The combined mass of the 14 red supergiants is ∼140 $M_{\odot}$. The whole cluster must surpass 100 times this mass, concentrated within a few arcminutes, to have survived to its likely present age. Figer et al. (2006) deduced a total mass of $(2–4) \times 10^4\ M_{\odot}$, based on isochrones using a Salpeter initial mass function, which is comparable to the virial mass estimated from these SiO maser observations. It is likely that the stars in the open cluster are gravitationally bound to the cluster, but expulsion of gases from the system reduces the gravitational energy of the system, which will eventually lead to cluster disruption (Geyer & Burkert 2001).

Eigenbrod et al. (2004) found optically that the radial velocity dispersion of 28 red giants in NGC 2477 (with a mass of about 5300 $M_{\odot}$) was about 0.93 km $^{-1}$, which is comparable to the velocity dispersions previously measured for other open

[2] Because of the smallness of the available SiO-emitting M supergiant sample, we assume here that the standard deviations are the same for M supergiants and AGB stars.

clusters, for example, 0.92 and 0.74 km $^{-1}$ for NGC 2099 and IC 4651.

3.3. *Masers in Red Supergiants*

Massive stars ($M \gtrsim 10\ M_{\odot}$) have relatively short main-sequence lives ($\lesssim 10^7$ yr). They evolve into neutron stars or black holes after the red supergiant phase through supernova explosions (Heger et al. 2003). An empirical formula (van Loon et al. 2005) was derived for the mass-loss rate of dust-enshrouded red supergiants and O-rich AGB stars; it fits equally well for LMC and Galactic objects. For a 10 $M_{\odot}$ red supergiant (with $L = 10^5\ L_{\odot}$ and $T_{\rm eff} = 2500$ K), this formula gives a mass-loss rate of $1.9 \times 10^{-4}\ M_{\odot}\ {\rm s}^{-1}$. In this case, the radius of the circumstellar envelope at $N_{\rm H_2} = 10^9\ {\rm cm}^{-3}$, where SiO maser pumping is most efficient (Bujarrabal 1994), is 5.3×10^{14} cm (assuming a velocity of 10 km s^{-1} for the expanding shell), which agrees with the observed radius of SiO masers in NML Cyg (Boboltz & Marvel 2000).

The *Midcourse Space Explorer* (*MSX*) band C (12.1 μm) flux densities of the Scutum cluster red supergiants with SiO masers are 10.7 and 14.2 Jy for stars F04 (G025.2512−00.1357) and F13 (G025.2830−00.1562), respectively. The SiO nondetections are fainter at 12.1 μm. Stars F01 and F02 were not resolved by *MSX*; the catalog gives a total flux density of 25.3 Jy in band C (G025.2755−00.1464). These two stars are the brightest cluster supergiants in the K band ($K = 4.96$ and $K = 5.03$; Figer et al. 2006). Star F13 is about 1 mag fainter ($K = 5.96$). The only cluster source detected in both SiO lines, F13, has the reddest color between K magnitude and *MSX* band C. The unresolved pair, F01 and F02, and F13 have the reddest *MSX* colors, taken as the ratio between the flux densities in bands C and E. This is broadly consistent with the correlation between IR color and SiO $v = 2$ to $v = 1$ line intensity ratio found in Nakashima & Deguchi (2003b). The bright objects with the heaviest mass loss are the maser hosts. This reflects differences in mass and evolutionary phase, which could be disentangled using a more detailed comparison between infrared data and the various masers detected.

4. CONCLUSION

We detected four out of 14 red supergiants in the Scutum star cluster in the SiO maser lines. The radial velocities and the velocity dispersion of the SiO masers lead to more accurate estimates of the cluster velocity and hence its distance, of 6.5 kpc, and its mass, of $\gtrsim 1.1 \times 10^4\ M_{\odot}$. These values are compatible with previous estimates based on the single OH maser peak, and the kinetic energy is comparable to the gravitational energy of this cluster. The presence of SiO masers and the large distance, and hence high luminosity, of the objects confirm their status as red supergiants. The relationship between SiO detections and infrared colors will lead to a deeper understanding of the subtle differences between these high-mass, high mass-loss rate stars.

The authors thank B. Murray Lewis of Arecibo Observatory and Jing-Hua He of ASIAA for reading the manuscript and for valuable comments. We also thank R. Bender for improving this Letter.

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