THE COOL SUPERGIANT POPULATION OF THE MASSIVE YOUNG STAR CLUSTER RSGC1

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ABSTRACT

We present new high-resolution near-IR spectroscopy and OH maser observations to investigate the population of cool luminous stars of the young massive Galactic cluster RSGC1. Using the 2.293 μm CO band-head feature, we make high-precision radial velocity measurements of 16 of the 17 candidate red supergiants (RSGs) identified by Figer et al. We show that F16 and F17 are foreground stars, while we confirm that the rest are indeed physically associated RSGs. We determine that star F15, also associated with the cluster, is a yellow hypergiant based on its luminosity and spectroscopic similarity to ρ Cas. Using the cluster’s radial velocity, we have derived the kinematic distance to the cluster and revisited the stars’ temperatures and luminosities. We find a larger spread of luminosities than in the discovery paper, consistent with a cluster age 30% older than previously thought (12 ± 2 Myr), and a total initial mass of (3 ± 1) × 10^4 M☉. The spatial coincidence of the OH maser with F13, combined with similar radial velocities, is compelling evidence that the two are related. Combining our results with recent SiO and H2O maser observations, we find that those stars with maser emission are the most luminous in the cluster. From this we suggest that the maser active phase is associated with the end of the RSG stage, when the luminosity-mass ratios are at their highest.

Subject headings: masers — open clusters and associations: general — stars: evolution — stars: late-type — supergiants

Online material: color figures

1. INTRODUCTION

The red supergiants (RSGs) represent a key evolutionary phase in the life cycle of stars with initial masses of ~8–30 M☉ (e.g., Meynet & Maeder 2000). Although comparatively brief, the mass-loss rate in this stage can be many orders of magnitude greater than on the main sequence (e.g., Repolust et al. 2004, van Loon et al. 2005), and the mass lost in the RSG phase can determine the terminal mass of the star, the appearance of the supernova (SN) explosion, and the nature of the stellar remnant (e.g., Heger et al. 2003).

The study of RSGs is hampered by low number statistics; until recently, only ~200 were known in the Galaxy and around 40 in the Large Magellanic Cloud (LMC). Further, the majority of these stars are isolated, and hence they have a variety of ages, initial masses, and metallicities. Ideally, we would like to study large numbers of RSG coeval clusters, where we can be confident that the variables of metallicity and initial stellar mass are fixed.

Two recent discoveries now present us with the opportunity to study statistically significant numbers of RSGs in such clusters. In Figer et al. (2006, hereafter FMR06) the discovery of an apparent cluster of 14 RSGs was presented, while Davies et al. (2007, hereafter DFK07) reported on the remarkable stellar population of a second cluster in the same region, which was shown to contain 26 RSGs. In order to use these two clusters as testbeds with which to study the pre-SN evolution of massive stars, we must first quantitatively study the properties of the stars within each.

In the case of the second cluster (RSGC2, also known as Stephenson 2), DFK07 used high-resolution spectroscopy to obtain accurate radial velocities of many stars in the region of the cluster and were able to separate proper cluster members from background/foreground stars. Further, from the radial velocities they made a quantitative discussion of the kinematic distance to the cluster, thus enabling them to determine the stars’ luminosities, temperatures, ages, and initial masses.

The details of the stellar properties of the first cluster (RSGC1) are less well constrained. In the discovery paper FMR06 showed with low-resolution spectra that the stars were all late-type; but with no radial velocity information, they relied on the stars’ similar near-IR colors to argue that the stars were all at the same distance. They determined this distance by associating a nearby OH maser, detected by Blommaert et al. (1994), with the RSGs. However, this maser was singly peaked; such masers are formed in the winds of RSGs and hence are typically doubly peaked, with separation twice the outflow speed. If the second peak was missed in the original observations, this would lead to an incorrect radial velocity for the cluster, and hence kinematic distance. Consequently, the cluster membership and the properties of the luminous cool stars of RSGC1 are poorly constrained when compared to RSGC2.

Here, we study the cool supergiants of RSGC1 with data of similar quality to those presented in DFK07 for RSGC2. We present high-resolution spectroscopy of the CO band-head feature of 16 of the 17 K-bright stars in the field identified in FMR06, allowing us to determine accurate radial velocities of the stars and establish the cluster membership. We also present new observations of the OH maser source OH 25.25–0.16, showing that it is indeed doubly peaked, and that the central radial velocity of the profile is consistent with the average stellar radial velocity. We use this value, in conjunction with contemporary Galactic rotation-curve parameters, to reappraise the distance to the cluster,
the stars' temperatures and luminosities, and the age and initial mass of the cluster.

We begin in § 2 with a description of the observations and data reduction steps, and we describe the results and analysis of the data in § 3. In § 4 we derive the cluster's age and mass and compare them with similar analyses of RSGC2. Finally, we use the stellar population of RSGC1 to investigate the maser active phase of RSGs.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Radio Observations and Data Reduction

OH maser observations at 18 cm were carried out with the VLA7 on 2006 May 25 in the AB configuration. The 256 channel spectrum had a bandwidth of 1.56 MHz giving a velocity resolution of 1.1 km s$^{-1}$ and was centered at $v_{LSR} = 100$ km s$^{-1}$. The observation consisted of a single pointing with J2000.0 coordinates of $18^h37^m53.2^s$, $-06^d53^m40^s$ and had a field of view of about 27'. The beam size was 3.5'' × 1.8''. The total integration time was 340 minutes, giving an rms error of about 4 mJy beam$^{-1}$ per 4 kHz channel.

The data were calibrated using the AIPS package. The flux and bandpass calibrator was 1331+305, while 1822 had a field of view of about 27'. The total integration time was 340 minutes, giving an rms error of about 4 mJy beam$^{-1}$ per 4 kHz channel.

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2.2. High-Resolution Spectroscopy

2.2.1. Observations

Observations were taken with NIRSPEC, the cross-dispersed echelle spectrograph mounted on Keck II, during the night of

7 The Very Large Array (VLA) is operated by the National Radio Astronomy Observatory under cooperative agreement with the National Science Foundation.
The arc lines were used to get initial estimates of the etalon-line wavelengths and hence of the etalon plate separation. The etalon-line wavelengths were then recomputed using the etalon equation and used to reestimate the wavelengths of the arc lines. The etalon thickness was fine-tuned in an iterative process until the residuals between the measured and predicted arc-line wavelengths across all orders were minimized.

After rectification, the spectra were extracted from each frame by summing the pixels across the trace in each channel. Shifts between spectra of up to 4 km s\(^{-1}\) (1 pixel), caused by the star not being quite in the center of the slit, were corrected for by cross-correlating the atmospheric CO\(_2\) feature at 2.05 \(\mu\)m in each spectrum.

The accuracy of the final wavelength solution is determined from the residuals between the observed and predicted arc-line wavelengths in the etalon-fitting process described above, and it is better than \(\pm\)4 km s\(^{-1}\). The internal error between spectra, from the CO\(_2\) telluric feature, is \(<\pm 1\) km s\(^{-1}\), so it is dominated by systematics in our analysis process which we estimate to be \(\pm 1\) km s\(^{-1}\) (DFK07).

3. RESULTS AND ANALYSIS

3.1. The Maser Source OH 25.25–0.16

As mentioned in § 1, the 1612 MHz OH maser forms in the outflows of RSGs, far above the stellar surface. The velocity profiles are therefore typically doubly peaked, with a separation twice the terminal velocity of the outflow centered on the star’s systemic velocity. However, when observed by Blommaert et al. (1994), OH 25.25–0.16 appeared only as a single peak with a radial velocity \(v_{\text{LSR}} = 102.2\) km s\(^{-1}\).

Our new observation of the OH maser source is shown in velocity space in Figure 2. Here it can be seen that we clearly detect the second peak. The flux-weighted mean velocities of the two peaks are 103.8 ± 0.1 and 138.1 ± 0.9 km s\(^{-1}\), calculated using all channels with emission greater than 5 \(\sigma\) above the background. The average velocity of the peaks is 120.9 ± 0.9 km s\(^{-1}\), consistent with the average velocities of the SiO masers in the cluster, 120.7 ± 3.2 km s\(^{-1}\), observed by Nakashima & Deguchi (2006). The implied outflow speed is 17.1 ± 0.6 km s\(^{-1}\), a typical outflow speed for RSGs (Richards & Yates 1998), and similar to the outflow speed of S Per (16 km s\(^{-1}\); Diamond et al. 1987), which occupies a location in the H-R diagram similar to that of the stars of RSGC1 (Gahm & Hultqvist 1976; see § 4 of this paper).

In Figure 1 we overlay a contour plot of the 1612 MHz emission on the 2MASS \(K\_s\)-band image of the cluster. We find the positional centroid of the OH maser to be 18\(^h\)37\(^m\)58.882\(^s\), 06\(\arcsec\)52\(\arcmin\)32.28\(\arcsec\) (J2000.0), with a positional uncertainty of 0.3\(\arcsec\). The J2000.0 position of the maser is consistent with previous measurements by Blommaert et al. (1994), which had a positional accuracy of 4\(\arcsec\). The maser is also spatially coincident with star F13, whose 2MASS coordinates are 18\(^h\)37\(^m\)58.908\(^s\), 06\(\arcsec\)52\(\arcmin\)32.11\(\arcsec\) (J2000.0), with a positional uncertainty of 0.06\(\arcsec\).

The central radial velocity of the OH maser is also consistent with the SiO observation of F13 by Nakashima & Deguchi (2006), \(v_{\text{LSR}} = 120.5 \pm 2.0\) km s\(^{-1}\), and with the CO bandhead radial velocity measurement of F13 presented in this paper.

\(^8\) This radial velocity was found from the average velocity of the high- and low-velocity edges. The centroid of the peak of this source was found to have a radial velocity of 116.5 ± 2 km s\(^{-1}\).
125.4 ± 4 km s⁻¹ (see § 3.2.1). From this evidence, it seems highly likely that the OH maser originates in the outflow of F13.

In addition to the OH maser, we also detect the continuum sources GPSR5 25.266−0.161, 25.252−0.139, and 25.237−0.15. These sources were shown conclusively to be extragalactic in origin by Trejo & Rodríguez (2006).

3.2. The High-Resolution Spectra

The high-resolution observations of the region around the CO band-head feature at 2.293 μm for 16 of the 17 K-bright stars are shown in Figure 3. All stars observed, with the exception of F15, show the feature strongly in absorption; F15 has it weakly in emission. Quantitative analysis of the high-resolution spectroscopy results is given below.

3.2.1. Stellar Radial Velocities

The radial velocities of each star serve two purposes: first, they allow us to distinguish between genuine cluster stars and foreground stars with similar colors; and second, they allow us to derive a kinematic distance to the cluster.

The differences in the radial velocities of the stars can be seen qualitatively in Figure 3; the blue edges of the CO band head in stars F16 and F17 are noticeably blueshifted compared to the others, which have very similar radial velocities.
In order to accurately quantify the radial velocities of the stars, we implemented the same technique as presented in Figer et al. (2003) and DFK07. We cross-correlated the spectra shown in Figure 3 with the high-resolution spectrum of Arcturus presented in Wallace & Hinkle (1996a), which had been degraded to the same spectral resolution as our data. For star F15, which has CO in emission, we inverted the spectrum before analysis. We experimented with isolating different spectral ranges during the cross-correlation to determine the robustness of our measurements. We found that the measured velocities were stable to within ±1 km s⁻¹, which we take to be the internal error between individual measurements. The absolute uncertainty on the measurements is limited by the accuracy of the wavelength solution, ±4 km s⁻¹ (see § 2).

We find that stars F01–F15 all have radial velocities in the range \( v_{\text{LSR}} \sim 115–125 \text{ km s}^{-1} \), while stars F16 and F17 have \( v_{\text{LSR}} \) values of 33 and 43 km s⁻¹, respectively. From this we conclude that the two faintest stars observed are foreground stars, while stars F01–F15 are physical members of the cluster. As F12 was unobserved, the status of this star is still unclear. We note that the CO absorption strengths of stars F16 and F17 are much lower than those of the RSGs and instead are more typical of less luminous stars. This is consistent with these stars being foreground objects.

The measured radial velocities of all stars observed are listed in Table 2. Also listed in Table 2 are the radial velocities, where available, determined from SiO maser emission by Nakashima & Deguchi (2006). We see that the two measurements of stars F02, F04, and F13 are within ~2 \( \sigma \), while for F01 it is ~3 \( \sigma \). As SiO masers are commonly thought to trace the stellar systemic velocity (Jewell et al. 1991), we would expect the two velocity measurements to agree well. However, we note that the observations of Nakashima & Deguchi (2006) may have been hampered by their beam size; their observations of F01, F02, and F13 have at least one other RSG within the beam FWHM. In the case of F04, which is well separated from the other RSGs, the CO band head and SiO maser measurements are in excellent agreement. As mentioned in § 3.1, the measured radial velocity of F13 is in excellent agreement with observations of the OH and SiO maser sources at the same location.

### 3.2.2. Distance to RSGC1

We take the mean radial velocity of the stars observed at high spectral resolution and compare it with the Galactic rotation curve, using the contemporary measurements collated by Kothes & Dougherty (2007). The mean radial velocity of the stars from the CO observations is 123.0 ± 1.0 km s⁻¹, with an uncertainty determined from Poisson statistics of the measurements. The absolute uncertainty on the radial velocity is therefore dominated by that in the wavelength solution, ±4 km s⁻¹. This compares well to the average radial velocity found by Nakashima & Deguchi (2006), ~120 ± 2 km s⁻¹, from their SiO maser observations and the central velocity of our new 1612 MHz OH maser observation, 120.9 ± 0.9 km s⁻¹.

In Figure 4 we compare our radial velocity to the Galactic rotation curve in the direction of \( l = 25.15^\circ, b = -0.15^\circ \). We use the distance to the Galactic center, \( D_{\text{gal}} = 7.5 ± 0.3 \) kpc (Eisenhauer et al. 2005), and solar rotational velocity \( \Theta_\odot = 214 ± 7 \text{ km s}^{-1} \) (Feast & Whitelock 1997; Reid & Brunthaler 2004). We use the uncertainties on these values to construct “maximal” and “minimal” rotation curves in Figure 4.

The cluster radial velocity actually extends beyond the asymptotic point of the curve; however, it lies well within the two “error” curves and therefore could simply be due to the uncertainties in \( D_{\text{gal}} \) and \( \Theta_\odot \). To determine the distance to the cluster, we take the average of the two points where the radial velocity intersects the maximal rotation curve. This gives us a kinematic distance to the cluster of \( 6.60 ± 0.89 \) kpc, slightly larger than the distance quoted in FMR06 when using the radial velocity of the singly peaked OH maser.

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### Table 2: Observed Data for RSGs

| ID (1) | \( v_{\text{LSR}} \) (km s⁻¹) | ND06' (km s⁻¹) | \( T_{\text{eff}} \) (K) | Spectral Type | \( A_k \) (6) | \( M_k \) (7) | \( \log (L_{\odot}/L_k) \) (8) |
|-------|-----------------|-----------------|-----------------|---------------|-----------------|-----------------|-----------------|
| F01   | 129.5           | 117.7           | 3450 ± 127      | M5            | 2.58 ± 0.09     | -11.75 ± 0.34   | 5.42 ± 0.12     |
| F02   | 114.2           | 119.7           | 3600 ± 127      | M2            | 2.83 ± 0.07     | -11.92 ± 0.30   | 5.56 ± 0.11     |
| F03   | 127.2           | ...             | 3450 ± 127      | M5            | 2.46 ± 0.09     | -11.28 ± 0.34   | 5.24 ± 0.12     |
| F04   | 121.2           | 124.3           | 3752 ± 117      | M1            | 2.46 ± 0.04     | -11.24 ± 0.28   | 5.32 ± 0.12     |
| F05   | 124.8           | ...             | 3535 ± 130      | M4            | 2.77 ± 0.08     | -11.36 ± 0.37   | 5.29 ± 0.14     |
| F06   | 120.7           | ...             | 3650 ± 127      | M5            | 2.19 ± 0.09     | -10.70 ± 0.30   | 5.00 ± 0.13     |
| F07   | 121.6           | ...             | 3605 ± 151      | M3            | 2.33 ± 0.12     | -10.81 ± 0.32   | 5.10 ± 0.14     |
| F08   | 128.2           | ...             | 3605 ± 151      | M3            | 2.84 ± 0.12     | -11.33 ± 0.36   | 5.30 ± 0.11     |
| F09   | 121.6           | ...             | 3399 ± 150      | M6            | 2.44 ± 0.08     | -10.92 ± 0.30   | 5.07 ± 0.12     |
| F10   | 122.0           | ...             | 3605 ± 151      | M3            | 2.45 ± 0.12     | -10.86 ± 0.36   | 5.12 ± 0.13     |
| F11   | 124.1           | ...             | 3535 ± 130      | M4            | 2.63 ± 0.08     | -11.03 ± 0.34   | 5.16 ± 0.14     |
| F13   | 125.4           | 120.5           | 4015 ± 140      | K2            | 3.19 ± 0.09     | -11.39 ± 0.34   | 5.45 ± 0.15     |
| F14   | 122.0           | ...             | 3605 ± 151      | M3            | 2.29 ± 0.12     | -10.25 ± 0.36   | 4.87 ± 0.14     |
| F15   | 120.8           | ...             | 6850 ± 350      | G0            | 2.65 ± 0.04     | -10.07 ± 0.36   | 5.36 ± 0.16     |
| F16   | 42.6a           | ...             | ...             | ...           | ...             | ...             | ...             |
| F17   | 33.2b           | ...             | ...             | ...           | ...             | ...             | ...             |

**Notes:**
- Col. (1): The stellar IDs (from FMR06).
- Col. (2) and (3): The radial velocity of each star (±4 km s⁻¹) and the radial velocity measured by Nakashima & Deguchi (2006), where available (±2 km s⁻¹).
- Col. (4): Effective temperature.
- Col. (5): Spectral type, accurate to ±2 subtypes.
- Col. (6): Derived extinction toward each star.
- Col. (7): Absolute K-band magnitude.
- Col. (8): Bolometric luminosity.

* We quote the Nakashima & Deguchi (2006) values measured by taking the average of the high- and low-velocity edges of the maser profiles.

* Stars F16 and F17 are determined to be foreground stars, while for F01 it is problematic due to the uncertainties in reddening and distance we derive no stellar parameters for these stars.
3.2.3. Effective Temperatures

To determine the spectral types of the RSGs, and hence their effective temperatures, we used the same empirical method described in DFK07. We compared the equivalent width ($W_{\lambda}$) of the CO band-head absorption with that of template stars taken from the catalogs of Kleinmann & Hall (1986) and Wallace & Hinkle (1996b, 1997). We defined a measurement region of 2.294–2.304 $\mu$m and defined the continuum as the median of the range 2.288–2.293 $\mu$m. We estimated the uncertainty by repeating the measurements with slightly adjusted continuum regions and found that measurements were stable to $\sim$1 Å, or $\sim$5%. To find the spectral types of the RSGs, we compared the $W_{\lambda}$ measurements with a linear fit to the $W_{\lambda}$ of the template stars as a function of spectral type. Using this method, we were able to determine spectral types to within $\pm$2 subtypes (see DFK07). In converting spectral type to effective temperature, we used the temperature scale of Levesque et al. (2005). The derived spectral types and effective temperatures for the RSGs are listed in Table 2.

For star F15 the method described above breaks down, as this star has CO in emission. The star’s radial velocity suggests that it is part of the cluster and hence a supergiant. It was assigned spectral type G6 I in FM06 and hence deemed a “yellow supergiant” (YHG) based on its weak CO band-head absorption. Given that this was only a marginal detection of CO absorption, here we reappraise the star’s spectral type.

Figure 5 shows the spectra of F15 on the two occasions it was observed. It can be seen that the CO band head, which was present in emission in May, was not detected at all in August. Over the rest of the star’s spectrum, no discernible variability is observed.

For comparison, Figure 5 shows similar template spectra of γ Cyg, spectral type F8 Iab, and α Sge, spectral type G1 III, which have been resampled to the same spectral resolution as our data (taken from Wallace & Hinkle 1997). Although admittedly α Sge has a lower luminosity class than that inferred for F15, it serves to give some insight into F15’s temperature. At spectral type G1, the CO band-head absorption is still seen, albeit weakly. The star also shows the atomic absorption lines of Al i, Fe i, Mg i, and Br γ. However, at this temperature molecular absorption, mostly from CN, can be seen as the undulating “noiselike” features throughout the spectrum. At spectral type F8, the CN and CO absorption are gone, while the atomic absorption lines remain.

From these comparison spectra, we assign a spectral type to F15 of G0, $\pm$2 subtypes, and hence an effective temperature of $T_{\text{eff}} = 6500–7200$ K. Indeed, the star is very similar spectroscopically to ρ Cas, one of the archetypical YHGs, which also shows transient CO emission/absorption (see spectra presented in Gorlova et al. 2006).

3.2.4. Extinction

The extinction toward each star is measured by comparing the 2MASS infrared colors of the stars to the intrinsic colors of supergiants with the same spectral type. For the RSGs we use the observations of Galactic stars with luminosity class Iab from Elias et al. (1985), while for F15 (the YHG) we use the tables of Koornneef (1983). We define the excess between the observed and intrinsic colors as the reddening toward each star. We convert this reddening to an extinction toward each star using the relationship of Rieke & Lebofsky (1985),

$$A_K = \frac{E_{2-0.6} - E_{2.1-2.2}}{(\lambda/\lambda_{2.1})^{1.53} - 1}.$$  \hspace{1cm} (1)

where $\lambda$ is the wavelength appropriate for the 2MASS $J$ or $H$ filters. To determine the uncertainty in each extinction measurement we derive extinctions for the upper and lower limits to each star’s spectral type. Where the difference between the derived $A_K(J - K_S)$ and $A_K(H - K_S)$ values is outside this uncertainty, we adopt half this difference as the error in the measurement.

Using this method, we find a median extinction of $A_K(J - K_S) = 2.58$ and $A_K(H - K_S) = 2.62$. Each has uncertainties of 0.07 magnitudes from Poisson statistics and is therefore in good agreement with the other. We adopt the mean of these measurements, $A_K = 2.60 \pm 0.07$, as the median extinction toward the cluster. We note that the extinction toward the YHG, $A_{K,F15} = 2.65 \pm 0.02$, is consistent with that derived for the RSGs.

The median cluster extinction is slightly lower than the $A_K = 2.74 \pm 0.02$ derived in FM06. We consider the latest measurement to be more reliable, due to the extra assumptions used in FM06: instead of dereddening each star according to the intrinsic colors appropriate for its spectral type, they dereddened all stars to the mean color of M supergiants from Elias et al. (1985). The ranges in colors of M supergiants are $\Delta(J - K) \sim 0.3$ and $\Delta(H - K) \sim 0.1$, which each correspond to $\Delta A_K \sim 0.2$ using equation (1). Hence, if the spectral types of the RSGs are asymmetrically distributed about the mean spectral type, this may affect the derived extinction by as much as 0.2 mag, consistent with the difference between the extinctions derived here and in FM06.

3.2.5. Luminosities

We take the extinctions toward each star derived in §3.2.4 in conjunction with the distance to the cluster estimated in §3.2.2 to determine the absolute $K_S$-band magnitudes of the stars. To convert these to bolometric luminosities ($L_*$) we interpolate over the contemporary bolometric corrections $BC_K$ for RSGs given in Levesque et al. (2005) for the stellar temperatures derived in §3.2.3.

The absolute uncertainty in each $L_*$ determination is $(\delta A_K^2 + \delta BC_K^2 + \delta D_{\text{cl}}^2)^{1/2}$. As we can confidently make the approximation that all the stars are located at the same distance, the uncertainty in distance $\delta D_{\text{cl}}$ can be neglected when analyzing the luminosity spread of the stars to infer the cluster’s age (see §4.1).
The uncertainties in both $A_K$ and $B_K$ are carried forward from the error in $T_{\text{eff}}$ and are determined by substituting the upper and lower limits to the stars' temperatures.

We list the stars' luminosities in Table 2, along with uncertainties which include the error in the cluster distance. The newly derived values are similar to those quoted in FMR06, typically within $\pm 0.3$ dex. As stated above, FMR06 used the same extinction toward all stars in the cluster, an approximation which breaks down if there are large variations in the interstellar extinction across the field or if a star has extra circumstellar extinction. Also, our high signal-to-noise ratio, high-resolution spectra give a more accurate picture of variations in CO equivalent width, and hence better constrained stellar temperatures—key in evaluating the stars' bolometric corrections. For these reasons,
we conclude that the bolometric luminosities derived here are more accurate than those quoted in FMR06.

3.2.6. Spectral Energy Distributions

Using the Galactic plane surveys of MSX and GLIMPSE (Egan et al. 2001; Benjamin et al. 2003), as well as 2MASS, we have collated IR photometry for all stars observed here. For the brighter stars, mid-IR photometry is unavailable due to the stars saturating in the images (e.g., F01 and F02), while fainter stars in crowded regions (e.g., F15) are dwarfed by brighter nearby stars (e.g., F09). We rejected all upper limit measurements and all detections fainter than 10\(\mu\)m. In all cases, the blackbodies provide excellent fits to the near-IR photometry, even in the case of F15, where a less accurate method of temperature estimation is possible. This serves to validate the stellar luminosities and temperatures of the stars derived above (cf. Fig. 13 of FMR06, where poorer fits to the IR photometry were obtained).

In all cases where photometry is available, the mid-IR MSX data show that the stars have considerable excess emission. This is indicative of warm circumstellar dust, a product of the high mass-loss rates of the stars. Also, the SEDs appear to show bumps around 12\(\mu\)m, which can be understood as silicate emission from the oxygen-rich dust. A detailed study of the circumstellar material around these objects will be the subject of a future paper.

4. DISCUSSION

4.1. Cluster Age

In Figure 7 we plot the derived temperatures and luminosities of the cool, luminous stars on an H-R diagram. Also plotted are...
isochrones taken from the stellar evolutionary models of Meynet & Maeder (2000), which include the effects of rotation and have initial rotational velocity set to 300 km s\(^{-1}\). As we can confidently make the approximation that all the stars are at the same distance, we do not include the error in distance on each data point. The magnitude of the error in \(L\) when this uncertainty is included is shown on the right side of the plot.

The figure shows that the temperatures and luminosity spread of the RSGs are well matched by the 12 Myr isochrone. The 10 Myr isochrone cannot reproduce the low-luminosity stars, while the 14 Myr isochrone is too faint to fit the high-luminosity stars. When the uncertainty in cluster distance is taken into account (\(\Delta D_{cl}\) in Fig. 7), the 10 and 14 Myr isochrones appear more reasonable. We experimented with different evolutionary models, namely, nonrotating models with varying mass-loss rates and metallicity (Schaller et al. 1992; Schaerer et al. 1993; Meynet et al. 1994). We found generally that the nonrotating models gave ages that were \(\approx 2\) Myr younger. We settled on an age estimate for RSGC1 of 12 \(\pm 2\) Myr.

We note that the YHG F15 does not lie on the 12 Myr isochrone in Figure 7. Fitting the star with the rotating Geneva isochrones, we get an age of 10 Myr (pre-blue loop) or 8 Myr (post-blue loop). For the specific models used in this analysis, the masses of RSGs in a 12 Myr old cluster do not experience a blue loop. However, the specific masses of stars which experience blue loops are extremely sensitive to the input physics, such as rotation (see Fig. 1 of Hirschi et al. 2004). Hence, a blue loop may be introduced for stellar initial masses relevant to RSGC1 simply by changing the rotational speed. In addition, it is likely that blue loops would be affected by the inclusion of extra physics (e.g., magnetic fields). In summary, we do not necessarily interpret F15’s location in the H-R diagram as evidence of cluster noncoevality; it could simply be that the input physics of the evolutionary models used in the analysis are not fine-tuned to this cluster.

If the RSGs of this cluster do experience some form of blue loop, then the position of F15 on the H-R diagram is consistent with it evolving away from the RSGs. A post-RSG nature for this star would make it a member of a very exclusive club; arguably, IRC +10420 is the only object which is widely accepted to be a post-RSG, although a case has also been argued for HD 179821.

Fig. 6—Continued
(see review of Oudmaijer et al. 2008). We note that F15 does not exhibit the same considerable IR excess or the bright maser emission of IRC +10420. This may be due to F15’s lower initial mass; the Geneva models imply \( \sim 18 M_\odot \) for F15, while the larger luminosity of IRC +10420 makes it consistent with a star of initial mass \( \sim 40 M_\odot \) (see also § 4.4).

The cluster age we derive is slightly greater than the age of \( \lesssim 9 \) Myr derived in FMR06. This previous estimate was determined by comparing the luminosity spread of the RSGs to that predicted by the nonrotating isochrones of Schaller et al. (1992) as a function of age. The more rigorous investigation of the stars’ luminosities in the present paper results in a larger luminosity spread for the RSGs, while the nonrotating models do not reproduce the higher luminosities. Much better agreement is found between the contemporary rotating models and the new luminosity estimates.

Finally, we remark that the observed temperatures of the stars are systematically cooler than the isochrones (see also Fig. 11, discussed below). This could be reconciled by increasing either the relative metal abundances or the stellar rotational velocities. Both lead to slightly increased stellar radii, the former due to the increased opacity of the envelope, the latter due to the lower effective gravities. A supersolar metallicity would certainly be consistent with the Galactic metallicity gradient and the cluster’s galactocentric distance (\( \sim 3 \) kpc). However, given the well-known disparities between observations and theory in the field of RSGs, we attach a cautionary note to any conclusions derived from this evidence. While recent progress has been made in uniting theory and observation at solar metallicity (Levesque et al. 2005), discrepancies still exist at subsolar metallicities (Levesque et al. 2006). The location in the Galaxy of the Scutum clusters would seem to make nonsolar metallicities likely. Accurate abundance measurements of the clusters would make them ideal testbeds for evolutionary models, as well as probes of the Galactic metallicity gradient.

4.2. Cluster Mass

To determine the cluster mass we employ the same Monte Carlo technique used in FMR06 and DFK07. We generate a synthetic cluster of a predefined initial mass, containing stars whose masses are randomly drawn from a distribution consistent with a Salpeter initial mass function (Salpeter 1955). Then, for a given cluster age, we determine the present-day masses, temperatures, and luminosities from the Geneva isochrones used in § 4.1. We then count the number of RSGs in the cluster, where we define a RSG as a star whose temperature is lower than 4000 K and with a luminosity greater than \( 10^4 L_\odot \). As this is a random process, we repeat each simulation 1000 times to reduce statistical noise.

In Figure 8 we plot the number of RSGs contained in a synthetic cluster as a function of cluster age for two initial cluster masses: 20,000 and 40,000 \( M_\odot \). The plot shows that significant numbers of RSGs begin to be seen after \( \sim 7 \) Myr; in clusters younger than this the post-MS stars are massive enough to evolve directly to the WN phase, skipping the RSG stage. Peaks in the number of RSGs are reached at \( \sim 14 \) and \( \sim 20 \) Myr; the dip in between is caused by the onset of a blue loop in the stars’ evolution for a narrow range of initial masses. The mean luminosity of the RSGs as a function of time decreases, as the initial masses of the stars in the RSG zone become smaller (see Fig. 7 and discussion in § 4.3). For a cluster containing 14 RSGs with an inferred age of \( 12 \pm 2 \) Myr (see above), we find that the initial mass of the cluster must be somewhere between these two, implying an initial mass of RSGC1 of \( (3 \pm 1) \times 10^4 M_\odot \).

Using the velocity dispersion of the RSGs, we can compare this value of the cluster’s initial mass to the cluster’s dynamical mass, under the assumption that the cluster is currently in virial equilibrium. The dynamical mass \( M_{\text{dyn}} \) is derived using the relation

\[
M_{\text{dyn}} = \frac{\eta \sigma^2 r_{\text{hp}}}{G},
\]

where \( r_{\text{hp}} \) is the half-light radius, \( \sigma^2 \) is the velocity dispersion, \( G \) is the gravitational constant, and \( \eta \) is a constant which depends on the stellar distribution with radius and is typically taken to be \( \sim 10 \) (see review in Introduction of Mengel et al. 2002).

For the velocity dispersion, we find \( \sigma^2 = 3.7 \) km s\(^{-1}\) after the internal uncertainty in the wavelength solution (\( \pm 1 \) km s\(^{-1}\)) has been subtracted in quadrature. To find the half-light radius, we plot the cumulative brightness profile of the cluster using stars F01–F15 as tracers of the cluster’s spatial distribution (see Fig. 9). We use a cluster center of \( 18^h 37^m 57.4^s, -6^\circ 52' 58.11" \) (J2000.0), the approximate midpoint of the cool stars. We experiment with moving the cluster center by up to \( 0.5' \), using different photometric bands, and using the luminosities derived in § 3.2.5 rather than the raw photometry. From all these methods we find that the cluster half-light radius is stable at \( 0.8'' \pm 0.1'' \). At the distance derived in § 3.2.2, this gives a cluster size \( r_{\text{hp}} = 1.5 \pm 0.3 \) pc.

Using these values, we find the dynamical mass of RSGC1 to be \( M_{\text{dyn}} = (5 \pm 1) \times 10^4 M_\odot \). Due to the extra uncertainty in the density parameter \( \eta \), we consider this to be an order-of-magnitude estimate only, which compares well to the initial cluster mass derived using evolutionary models.

4.3. Comparison of the Two RSG Clusters

Given that, until recently, the largest number of RSGs in any one cluster was five, the discovery of the two Scutum RSG clusters lying so close to one another is remarkable. After applying the same analysis techniques to each cluster, we summarize the physical parameters of RSGC1 and RSGC2 in Table 3.

The radial velocities of each cluster put them at the tangential point of the Galactic rotation curve, with galactocentric distances of \( 3–4 \) kpc. The clusters are separated from one another
by $0.8^{+1.6}_{-0.7}$ kpc. Their proximity, combined with their similar ages, suggests that they were both formed in a region-wide starburst phase some $10$–$20$ Myr ago, and that the chemical abundances of their natal material should be similar.

First-order evidence of uniform metallicity between the clusters comes from the median spectral type of the RSGs, which is M3 in each cluster. The average spectral type of the RSGs has been shown to be dependent on environment, shifting gradually to later types with increasing metallicity; averages of K5, M1, and M2 were found for the SMC, LMC, and Galaxy, respectively (Elias et al. 1985; Massey & Olsen 2003). Proposed physical explanations for this include (1) reduced metallicity leading to lower envelope opacities, increased stellar radii, and hence systematically lower effective temperatures; or (2) the effect of lower metal abundances on the strengths of the diagnostic TiO lines. Regardless, the average spectral type of M3 for the two Scutum clusters would seem to suggest that they have similar, possibly supersolar, metallicities. The chemical abundances of the stars in these clusters will be the subject of a future paper.

Both from the analysis of evolutionary models and the velocity dispersion, we find similar masses for each cluster; the factor of 2 difference in the number of RSGs is caused by the difference in mass ranges of cool stars as a function of time. From the luminosity and mass ranges of cool stars as a function of time. The Galactic center; col. (8), initial mass range of the RSGs within the clusters. RSGC2 values come from DFK07.

One aspect of RSG evolution which the two Scutum RSG clusters allow us to study is the onset of the maser active phase.Masers are often observed in “extreme” cool stars, e.g., the RSGs VY CMa, NML Cyg, and S Per (see Richards & Yates 1998 and references therein), which are also synonymous with large IR excesses. In the standard picture, these phenomena are caused by episodes of high mass loss, producing large amounts of circumstellar material which gives rise to the IR excess. The masers themselves originate in the outflowing material. The SiO 43 GHz maser is formed low in the wind at higher temperatures; at larger radii the formation of dust grains leads to a depletion of SiO. In the SiO maser-forming region the outflow velocity is low, and hence SiO masers typically have radial velocities similar to the stellar systemic velocity, $v_{\infty}$ (Jessell et al. 1991). The H$_2$O 22 GHz maser forms higher in the wind and typically has peaks at many velocities within $v_{\infty}$, where $v_{\infty}$ is the wind’s terminal velocity (typically around 10–30 km s$^{-1}$). At larger radii still, H$_2$O is photodissociated to OH, giving rise to the 1612 MHz OH maser. Here the outflow has reached its terminal velocity, giving the line profile its typical double-peaked morphology (where the separation of the peaks is $2v_{\infty}$ and the centroid is $v_{\infty}$). For a more comprehensive review of masers in luminous cool stars, see Habing (1996).

### Table 3: Properties of the Two Scutum RSG Clusters

| Cluster  | $M_{\text{int}}$ (evol) ($\times10^4 M_\odot$) | $M_{\text{bol}}$ ($\times10^4 M_\odot$) | Age (Myr) | $d$ (pc) | $D_\odot$ (kpc) | $D_{\odot}$ (kpc) | $M_{\text{init}}$(RSGs) ($M_\odot$) |
|----------|------------------------------------------|--------------------------------------|-----------|---------|----------------|------------------|----------------------------------|
| RSGC1    | $3 \pm 1$                               | $5 \pm 1$                            | $12 \pm 2$| $1.5 \pm 0.3$ | $6.60 \pm 0.89$ | $3.2$            | $18^{-4}_{+5}$                   |
| RSGC2    | $4 \pm 1$                               | $6 \pm 4$                            | $17 \pm 3$| $3.2^{+1.2}_{-0.7}$ | $5.83^{+1.91}_{-0.76}$ | $3.5$            | $14 \pm 2$                     |

Notes.—Col. (1), cluster name; col. (2), total initial cluster mass derived from evolutionary models; col. (3), cluster mass derived from stellar velocity dispersion; col. (4), cluster age; col. (5), cluster diameter; col. (6), cluster distance; col. (7), distance from cluster to the Galactic center; col. (8), initial mass range of the RSGs within the clusters. RSGC2 values come from DFK07.
It is unclear as to whether the maser stage is one which all RSGs will go through, or whether only extreme objects will pass through this phase. Much work has been done on the detailed physical conditions under which masers form (see review of Habing 1996); however, in a simplified picture one may say that the presence of the different masers is determined by the wind density, i.e., by mass-loss rate and pulsations. For an increasing mass-loss rate, the critical density will be gradually reached in the formation zones of each transition, while stellar pulsations will create density contrasts in the outflow conducive to population inversions. That is to say, we expect to see maser emission from those RSGs which have the strongest mass-loss rates and are pulsationally unstable.

Mass loss from RSGs is driven by radiation pressure on dust grains in the outer atmosphere and depends on the star’s effective temperature (cool enough to allow dust to form) and luminosity (high radiation pressure; van Loon et al. 2005). Hence, we may expect to find masers in high-mass RSGs which have higher luminosities, while among a coeval sample of RSGs one may expect to see masers in those objects furthest along their evolution, where their path on the H-R diagram takes a sharp upturn (see Fig. 7). Further, as masers are linked to stellar pulsations, we may expect to find masers in unstable stars, i.e., stars with high \( L_*/M_* \) ratios that are evolving closer to the Humphreys-Davidson limit at \( L_* \sim 10^{5.7} \) \( L_\odot \) (Humphreys & Davidson 1979). This zone of the H-R diagram is often linked to the so-called modified Eddington limit, when the contributions of atomic/molecular transitions to the continuum opacity are included when calculating the Eddington luminosity.

To investigate the presence of masers in RSGs, in Figure 11 we plot an H-R diagram of the RSGs in RSGC1 and indicate those stars which are maser sources. In addition to the OH maser observations presented here, SiO and H$_2$O maser observations of RSGC1 were also taken by Nakashima & Deguchi (2006). They found that stars F01, F02, F04, and F13 were spatially coincident with SiO emission, while they concluded that the H$_2$O maser emission they found had likely come from F13.

The figure shows that it is the most luminous stars of the cluster which exhibit maser emission. Further, F13, which is the source of SiO, H$_2$O, and OH masers, appears to be at the point of evolving back toward the blue. The figure therefore appears to support the hypothesis that maser emission activates (or becomes strong enough to be observed) in the latest stages of RSG evolution, when the star’s mass-loss rate is highest and the star becomes unstable to pulsations.

This hypothesis could be tested with a study of the second Scutum RSG cluster, RSGC2. This cluster also has many RSGs, and so we are again seeing stars in both the earlier and later RSG stages. As mentioned in §4.3, the stars in RSGC2 are less luminous than those of RSGC1 and hence further from the Humphreys-Davidson limit. Although they likely have lower initial masses, they have lower \( L_*/M_* \) ratios. Thus, we may not expect to see maser emission from these stars, especially those with lower \( L_* \). A comprehensive maser study of the RSGC2 region would be able to test at which phase of RSG evolution stars become maser active, while nondetections would place lower limits on the initial mass requirements to pass through the maser active phase.

Finally, we note that the YHG F15 is not observed to have maser emission, unlike the prototype post-RSG IRC +10420. Masers are rarely observed around stars hotter than \( \sim 4000 \) K, and the presence of maser emission in IRC +10420’s outflow is commonly accepted as evidence of its rapid evolution away from the RSG phase. That no maser is observed in F15 may be indicative of a lower wind density while in the RSG phase, due to

10 The large beam size of the 22 GHz H$_2$O maser, 73" overlaps several other stars in the cluster. However, as these masers are often observed in stars with maser emission from SiO, and as the central velocity of the H$_2$O maser was consistent with that from the SiO maser emission of F13, Nakashima & Deguchi (2006) concluded that F13 was likely to be the origin of the H$_2$O maser emission.
its lower initial mass (~18 $M_\odot$ compared to ~40 $M_\odot$ for IRC +10420).

5. CONCLUSIONS

We have presented a comprehensive investigation into the physical properties of the luminous cool stars in the massive cluster RSGC1. Using high-resolution spectroscopy we have accurately measured the cluster’s radial velocity, derived its kinematic distance, and reappraised the stars’ temperatures and luminosities. We find a larger luminosity spread than in the discovery paper, which is well fitted by a cluster age of 12 Myr and cluster mass of $(3 \pm 1) \times 10^4 M_\odot$. The mass is similar to that of the nearby cluster RSGC2, and we suggest that the difference in the number of RSGs in each is due to the separation in cluster ages, with RSGC2 being somewhat older. This implies that the initial masses of the RSGs in each cluster are different, which we determine to be ~18 $M_\odot$ for RSGC1 and ~14 $M_\odot$ for RSGC2. The clusters therefore allow the study of RSG evolution as a function of initial mass while constraining the variable of metallicity. Finally, with new 1612 MHz radio observations we find compelling evidence that the OH maser is associated with star F13, and by collating recent maser observations of the cluster we argue that the maser active phase is associated with stars in the latter stages of RSG evolution.

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1028  DAVIES ET AL.