MASSIVE STARS IN THE QUINTUPTET CLUSTER

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ABSTRACT

We present near-infrared photometry and K-band spectra of newly identified massive stars in the Quintuplet cluster, one of the three massive clusters projected within 50 pc of the Galactic center. We find that the cluster contains a variety of massive stars, including more unambiguously identified Wolf-Rayet stars than any cluster in the Galaxy, and over a dozen stars in earlier stages of evolution, i.e., luminous blue variables (LBVs), Ofpe/WN9, and OB supergiants. One newly identified star is the second luminous blue variable in the cluster, after the “Pistol star.” Although we are unable to provide certain spectral classifications for the five enigmatic Quintuplet-proper members, we tentatively propose that they are extremely dusty versions of the WC stars found elsewhere in the cluster and similar to the dozen or so known examples in the Galaxy. Although the cluster parameters are uncertain because of photometric errors and uncertainties in stellar models, i.e., extrapulating initial masses and estimating ionizing fluxes, we have the following conclusions. Given the evolutionary stages of the identified stars, the cluster appears to be about 4 ± 1 Myr old, assuming coeval formation. The total mass in observed stars is ~10⁵ M☉, and the implied mass is ~10⁴ M☉, assuming a lower mass cutoff of 1 M☉ and a Salpeter initial mass function. The implied mass density in stars is greater than or similar to a few thousand M☉ pc⁻³. The newly identified stars increase the estimated ionizing flux from this cluster by about an order of magnitude with respect to earlier estimates, to 10^{30.9} photons s⁻¹, or roughly what is required to ionize the nearby “Sickle” H II region (G0.18 − 0.04). The total luminosity from the massive star cluster is ≈10^{5.5} L☉, enough to account for the heating of the nearby molecular cloud, M0.20−0.033. We propose a picture that integrates most of the major features in this part of the sky, excepting the nonthermal filaments. We compare the cluster to other young massive clusters and globular clusters, finding that it is unique in stellar content and age, except, perhaps, for the young cluster in the central parsec of the Galaxy. In addition, we find that the cluster is comparable to small “super star clusters.”

Subject headings: Galaxy: center — H II regions — open clusters and associations: individual (Quintuplet cluster) — stars: Wolf-Rayet

1. INTRODUCTION

Three extraordinary bursts of star formation have produced young clusters in the Galactic center (GC) in the past 10 Myr (Figer, Morris, & McLean 1996, hereafter FMM96; Krabbe et al. 1995; Nagata et al. 1995; Cotera et al. 1996; Serabyn, Shupe, & Figer 1998). In addition to their location in the Galaxy, these clusters are also special for being the most massive young clusters in our Galaxy. They offer us the opportunity to investigate massive star formation in molecular clouds with extrasolar metallicity, large internal turbulent velocities, and strong magnetic fields. The many stars in each cluster may also finally provide the necessary statistics to investigate the existence of a true upper mass cutoff to the initial mass function (IMF) in the Galactic center.

The Quintuplet cluster is one of these massive clusters, and it is located approximately 30 pc, in projection, to the northeast of the Galactic center (Glass, Catchpole, & Whitelock 1987). In addition to the five bright stars for which the Quintuplet was named (Nagata et al. 1990; Okuda et al. 1990), there is a clustering of hundreds of other stars in the vicinity. Our JHK color composite (Fig. 1) clearly shows a concentration of bright stars spanning a diameter of ≈50°. Beyond this, cluster members are indistinguishable in continuum images from the already crowded field of stars in this part of the sky.

The cluster was originally observed as one or two sources in various infrared surveys (see §1 in Okuda et al. 1990 for a summary), until the late 1980s, when three groups finally separated the cluster into a dozen or so sources (Nagata et al. 1990; Okuda et al. 1990; Glass, Moneti, & Moorwood 1990). Nagata et al. (1990) and Okuda et al. (1990) noted that five of the cluster stars are extraordinary in their large luminosities, very cool spectral energy distributions, and lack of intrinsic spectral features. They speculated that these objects might be young, dust-enshrouded stars.

Since then, many other cluster members have been identified as post–main-sequence descendants of O stars (Moneti, Glass, & Moorwood 1994, hereafter MGM94; Geballe et al. 1994; Harris et al. 1994; Figer, McLean, & Morris 1995, hereafter FMM95; FMM96; Cotera et al. 1996; Figer et al. 1998a). Most of these cluster stars are OB supergiants with strong winds, i.e., Wolf-Rayet stars and luminous blue variables (LBVs). It is now clear that the Quintuplet cluster is very massive and that its members form a true physical group.

The Quintuplet cluster is proving to be key in understanding questions to many important questions: (1) Is the cluster in the inner parsec of the Galaxy really “unique,” i.e., are extraordinary physical processes or continuous star formation scenarios required to explain the stellar content of the central cluster? (2) Do hot stars in the Quintuplet ionize the nearby H II regions, G0.18 − 0.04 (the “Sickle”)

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and G0.15−0.05 (the “Pistol”)? (3) Does the IMF in the Galactic center favor the formation of high-mass stars? (4) Are stars in the Quintuplet consistent with stellar evolution models that predict that WR/(WR + O) and WC/(WR + O) should be elevated in higher metallicity regions?

In this paper, we expand upon the work of FMM96 and Figer et al. (1998a) in showing that the Quintuplet cluster is extraordinary for its membership of massive evolved stars. We present new JHK' narrowband L(nbL) photometry and K-band spectroscopy of the massive stars in the Quintuplet with the goal of answering some of the aforementioned questions. In § 2 we describe the observations and data reduction. In § 3 the spectral classifications are presented. We “sum” the properties of the individual stars in § 4 to infer cluster properties, i.e., mass, age, and ionizing flux; the latter is used to argue that Quintuplet stars are ionizing the nearby H II regions. We compare the cluster properties to those of other massive clusters in the Galaxy and Magellanic Clouds in § 5, arguing that it is a “near-twin” to the young cluster in the central parsec of the Galaxy (hereafter referred to as the “Central cluster”) and is an older “brother” of the nearby Arches cluster. In this section, we present a consistent picture to account for the proximity of the Quintuplet, Pistol, and Sickle. We also interpret the Quintuplet cluster as a “super star cluster,” i.e., those seen around other galaxies. Finally, in § 6 we present conclusions, noting that the current sample of stars does not permit an investigation of the IMF or massive star evolu-
tionary models. Such investigations await our Hubble Space Telescope (HST)/NICMOS data (Figer et al. 1999a).

2. OBSERVATIONS AND DATA REDUCTION

2.1. Observations

All data were taken with the UCLA double-beam near-infrared camera (McLean et al. 1993, 1994) at the University of California Observatories’ 3 m Shane telescope, producing a plate scale of 0:7 pixel\(^{-1}\). A grism was inserted into the beam, in conjunction with a 2 pixel wide slit mask, to produce spectra covering the K-band atmospheric window and having \( R = \lambda / \Delta \lambda \approx 525 \) (Figer 1995). Table 1 gives the identifications and coordinates for the target stars and the dates when the spectra were obtained. The numbering results from a count of stars in the 1994 July 20 \( K'\)-band image, proceeding from east to west and south to north. Stars 577 and 578 are located outside of this image, so they are numbered sequentially starting with the next integer after the last star in the image. Figure 1 is a \( JHK' \) color composite of a region centered on the cluster. Figures 2a–2d contain individual \( JHK'nbL \) images. Figure

TABLE 1

| ID Number | Nagata et al. 1990 | Moneti, Glass, & Moorwood 1994 | R.A.\(^{a}\) (s) | Decl.\(^{b}\) (arcmin arcsec) | Dates Observed |
|-----------|-------------------|-------------------------------|----------------|--------------------------|----------------|
| 76......... | ...               | ...                           | 5.1            | 49.116                   | 1994 Jul 26    |
| 134\(^{c}\) | ...               | seren                         | 4.8            | 48.569                   | 1994 Jul 26    |
| 151       | ...               | ...                           | 4.4            | 48.538                   | 1995 Aug 5     |
| 157       | ...               | ...                           | 3.5            | 48.520                   | 1995 Aug 5     |
| 178       | ...               | ...                           | 9.3            | 48.462                   | 1995 Aug 5     |
| 192       | ...               | 7                             | 6.2            | 48.436                   | ...            |
| 197       | ...               | ...                           | 4.9            | 48.429                   | 1995 Aug 5     |
| 211\(^{d}\) | GCS4              | 3                             | 5.5            | 48.390                   | ...            |
| 231\(^{e}\) | GCS3-2            | 2                             | 4.3            | 48.340                   | ...            |
| 235       | G                 | 11a                           | 4.8            | 48.335                   | 1995 Aug 5     |
| 240       | ...               | 8                             | 5.5            | 48.312                   | ...            |
| 241       | F                 | 10                            | 4.7            | 48.302                   | 1995 Aug 5     |
| 242       | ...               | ...                           | 4.1            | 48.300                   | 1995 Aug 5     |
| 243       | GCS3-4            | 1                             | 3.7            | 48.299                   | ...            |
| 250       | B                 | 6                             | 5.0            | 48.279                   | 1995 Aug 5, 1996 Aug 20 |
| 251       | GCS3-1            | 4                             | 4.4            | 48.276                   | ...            |
| 252       | ...               | ...                           | 4.1            | 48.271                   | 1995 Aug 5     |
| 256       | ...               | ...                           | 6.1            | 48.252                   | 1995 Aug 5     |
| 257       | D                 | 13                            | 4.8            | 48.255                   | 1995 Aug 5     |
| 258       | GCS3-3            | 9                             | 3.9            | 48.247                   | ...            |
| 269       | A                 | ...                           | 5.1            | 48.231                   | 1995 Aug 5     |
| 270N      | C                 | 5                             | 4.7            | 48.213                   | ...            |
| 270S      | C                 | 15                            | 4.7            | 48.219                   | 1995 Aug 5     |
| 274\(^{f}\) | ...               | ...                           | 7.1            | 48.224                   | 1995 Aug 5     |
| 276       | ...               | ...                           | 3.0            | 48.223                   | 1995 Aug 5     |
| 278       | E                 | 12                            | 4.7            | 48.275                   | 1995 Aug 5     |
| 301       | ...               | ...                           | 5.6            | 48.150                   | 1995 Aug 5, 1996 Aug 20 |
| 307       | ...               | ...                           | 5.1            | 48.135                   | 1995 Aug 5, 1996 Aug 20 |
| 309       | ...               | ...                           | 7.1            | 48.121                   | 1995 Aug 5     |
| 311       | ...               | ...                           | 3.3            | 48.125                   | 1995 Aug 5, 1996 Aug 20 |
| 320       | ...               | ...                           | 3.7            | 48.97                    | 1994 Jul 26    |
| 344       | ...               | ...                           | 6.3            | 48.26                    | 1995 Aug 5, 1996 Aug 20 |
| 353E      | ...               | ...                           | 0.8            | 47.583                   | 1995 Aug 3     |
| 358       | ...               | ...                           | 6.2            | 47.582                   | 1995 Aug 5     |
| 362       | ...               | ...                           | 7.6            | 47.566                   | 1996 Aug 20    |
| 381       | ...               | ...                           | 3.1            | 47.522                   | 1995 Aug 5     |
| 406       | ...               | ...                           | 3.5            | 47.435                   | 1995 Aug 5, 1996 Aug 20 |
| 577       | ...               | ...                           | 53.8\(^{g}\)   | 51.41                    | 1996 Jul 5     |
| 578       | ...               | ...                           | 57.8          | 48.47                    | 1996 Jul 5     |

Note.—The Quintuplet-proper members have “GCS” designations in col. (2). Coordinates are in equinox 1950.0 and are estimated from our images, based upon the coordinates for “q3” in Nagata et al. 1993. Col. (6) refers to when spectra were obtained.

\(^{a}\) Seconds in right ascension offset from 17\(^{h}\)43\(^{m}\).

\(^{b}\) Minutes and seconds of arc in declination from –28\(^{\circ}\).

\(^{c}\) The Pistol star (Figer et al. 1998b). *Pistol Source A* in Cotera et al. 1996. Object 25 in Nagata et al. 1993.

\(^{d}\) Object 26 in Nagata et al. 1993.

\(^{e}\) Object 24 in Nagata et al. 1993.

\(^{f}\) Pistol Source B in Cotera et al. 1996.

\(^{g}\) This star falls outside of our K’-band image. Coordinates are for object 21 in Nagata et al. 1993. R.A. is in seconds of offset from 17\(^{h}\)42\(^{m}\).

\(^{h}\) This star falls outside of our K’-band image. Coordinates are for object 42 in Nagata et al. 1993. R.A. is in seconds of offset from 17\(^{h}\)42\(^{m}\).
fig. 2. — (a) J-band image of Quintuplet cluster, covering 3′ × 3′. (b) H-band image of Quintuplet cluster, covering 3′ × 3′. (c) $K'$-band image of Quintuplet cluster, covering 3′ × 3′. (d) nbL-band image of Quintuplet cluster, covering 3′ × 3′. The diagonal lines are artifacts from bad pixels in the array.

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3a shows an alternate gray-scale stretch of the $K'$ image shown in Figure 2c at an expanded scale. Figure 3b gives a "zoomed" finder chart for the brightest cluster stars in Figure 3a, which were included in the slit-scan data cube (see below).

2.2. Photometry

Photometry was extracted from two sets of images; the first set contains $H$- and $K'$-band images obtained on 1994 July 20, and the second set contains $JHK'nbL$ images obtained on 1996 July 4. The seeing generally produced images with less than 2 pixels (1′.4) full width at half-maximum. The data were reduced according to the procedures in Figer (1995). In summary, bias structure and dark current were removed from target frames by subtracting "bias + dark" calibration frames; these images had the same exposure parameters as the target frames, except that an opaque mask was inserted into the beam when they were taken. Variations in system efficiency, especially due to pixel-to-pixel differences in quantum efficiency, were removed by dividing the target image by a "flat-field" image; these images were constructed by forming the median of a stack of frames, each taken with the telescope in a slightly different position. This "dithering" serves to eliminate objects in the final flat-field frame.

Final photometry was extracted using DAOPHOT, a point-spread function fitting routine in IRAF. Photometric apertures with 4′2 diameter were used, i.e., 3 times the size of the seeing disk. The results are listed in Table 2. $K$ magnitudes were converted from $K'$ using the relation in Wainscoat & Cowie (1992). We observed atmospheric standards from the list in Elias et al. (1982). The inferred zero points from the July 4 images varied considerably as a function of

2 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
time and air mass, i.e., the night was not photometric. We adopted the flux measurements in the first data set (Figer 1995), instead, for the $H$ and $K$ bands; the effective zero points were estimated by minimizing the difference between the average photometry in the two data sets for the stars listed in Table 2. The $J$ and $nbL$ zero points were extrapolated to high air mass from the observations of the standard stars. We assess a photometric error of $\pm 0.2$ mag for all bands.

2.3. Spectra

The spectra cover most of the $K$ band and were reduced using procedures described in Figer, McLean, & Najarro (1997). Some of the spectra were extracted from a slit-scan data cube covering a 1' (east-west) $\times$ 2' (north-south) area, as shown in Figure 4. The telescope was stepped by 1" along the east-west direction between exposures. Star 211 (Quintuplet star 3 according to MGM94) was used as an atmospheric standard in all cases. The observations presented in this paper, and those of others (Okuda et al. 1990; MGM94; Nagata, Kobayashi, & Sato 1994; Figer et al. 1998b), show that 211 is spectroscopically featureless. The divided spectra were multiplied by a blackbody function, with $T = 630$ K, to correct for the intrinsic energy distribution of 211. We have found that this temperature is appropriate for the apparent $K$-band spectral energy distribution of 211 (see Fig. 1 in Figer et al. 1998b). The spectra generally have signal-to-noise ratio $S/N \gtrsim 30$, i.e., features having $|\text{EW}| > 3$ Å should be detectable at a level of a few times the noise in the continuum.

3. SPECTRAL CLASSIFICATIONS

Our spectral classifications are based upon $K$-band spectra. The final classifications are given in Table 3, along with the estimated luminosity and ionizing flux for each star. The Wolf-Rayet (W-R) stars were classified using the atlas of Figer et al. (1997; $R \approx 525$). Their montage of Galactic W-R $K$-band spectra has been reproduced in Figure 5. The “OB I” stars were classified using the atlases of Hanson, Conti, & Rieke (1996) and Tamblyn et al. (1996).
3.1. Wolf-Rayet Stars

Figure 5 shows that the emission lines for the Galactic W-R stars tend to follow the expected trend of greater equivalent width for higher ionization species with earlier subtype. Spectral classification based upon K-band spectra is more effective in distinguishing different subtypes among the WN sequence than the WC sequence. WR 108 (the only bona fide WN9 star in the sample) lacks He II emission at 2.189 μm, whereas WN8 stars show a hint of it. This is the strongest feature in earlier WN stars. This line, along with the 2.11 μm feature (He I/C III/N III), allows accurate discrimination to within one subtype for the WN sample in Figure 5. The WC stars tend to have a similar spectra except for the latest types (WC8 and WC9). This degeneracy can be partially lifted by measuring flux in the 3.09 μm He II line (Figer 1995). WR 112 and WR 118 have featureless spectra, presumably due to dilution by dust emission (Williams, van der Hucht, & Thé 1987).

The W-R stars in our sample were classified by comparing their spectra (Figs. 6a–6d) to the spectra in Figure 5 and by comparing their flux excesses at 3.09 μm to those measured in Galactic W-R stars. The newly identified WN9 stars in the Quintuplet cluster, 256 and 274, have line widths similar to 320 (FMM95-1), and they lack He II emission (2.189 μm). The new WN6 star, 353e, has prominent emission at 2.189 μm, which is comparable to the emission-line strength near the 2.166 μm He II line; it also has a considerable excess at 3.09 μm.

The new WC stars all have similar spectra, lacking the prominent emission at 2.058 μm, which is usually seen in WC9 stars, i.e., 76 (FMM95). Two of the stars, 309 and 235, are classified as earlier than WC8 for their excesses at 3.09 μm, whereas 151 has very little excess there. Together, the WN6 and the two “<WC8” stars are among the hottest identified stars within 50 pc of the Galactic center, although their ionizing fluxes are quite meager owing to their small radii (Crowther & Smith 1996).

3.2. OB Supergiants

Spectra for the OB supergiants are shown in Figures 7 and 8. The “<B0 I” stars have a featureless continuum, i.e., no features having |EW| > 2 Å. Their K-band magnitudes
put them in the supergiant class, and their featureless spectra are consistent with a classification earlier than B0 I. Spectra for later types, i.e., A or F supergiants, have a relatively strong Brackett-γ line in absorption or emission (Hanson et al. 1996). All other OB supergiants were classified for the strengths of the three primary lines in the K band: Brackett-γ (2.166 μm), He I (2.058 μm), and He I (2.112/2.113 μm). The strength of the 2.058 μm feature is suspect when there appear to be features near 2.312 and 2.370 μm; all three features, when present, may be due to incomplete atmospheric correction. The OB I stars have Brackett-γ and He I (2.058 μm) in emission with He I (2.112/2.113 μm) in absorption; again, the 2.058 μm line might be contaminated by improper atmospheric correction, as described above. The spectra are similar to those of HD 207329 (B1.5 IB:e; Tamblyn et al. 1996) and BD +36°4063 (ON9.7 Ia; Tamblyn et al. 1996 and Hanson et al. 1996); it should be noted, though, that ON9.7 Iab stars in Hanson et al. (1996) have all three diagnostic features in absorption. Some Galactic center stars also have similar spectra (cf. IRS 16NE, IRS 16NW, and IRS 33E in Genzel et al. 1996). The early B I stars were classified by measuring the equivalent widths in these three spectral lines, all in absorption, and comparing these values to those in the atlases. The Ofpe/ WN9 stars have been previously classified (Geballe et al. 1994; Figer 1995; Cotera et al. 1996).

3.3. The Quintuplet-proper Members

The nature of the Quintuplet-proper members (QPMs) has remained a mystery since their discovery. They are very bright in the infrared, \( m_K \approx 6 \) to 9, and have cool apparent spectral energy distributions, i.e., infrared color temperatures between \( \approx 600 \) to 1000 K. We present dereddened SEDs with blackbody fits in Figures 9a–9e. The fits have been made to the data, dereddened by \( A_K = 2.7 \), instead of the higher value (see § 4) derived for the other cluster stars; this has been arbitrarily done because the lower extinction value is better fit by a single-temperature blackbody. There is no a priori reason to expect that the emission should follow a single-temperature blackbody. In fact, the increased dereddened J-band flux that the stars would have if dereddened by \( A_K = 3.2 \) might be an indication of a rising
spectrum for the underlying photosphere. We find good fits for temperatures of 780 to 1315 K. Glass et al. (1990) performed a similar analysis and found somewhat cooler temperatures due to the smaller extinction value they assumed. After dereddening, their integrated infrared luminosities are in the range $10^{4.3}$ to $10^{5.2} L_\odot$, yet no spectral features characteristic of supergiants have been found. In fact, the objects are spectroscopically featureless at all wavelengths observed, making their spectral classification ambiguous (Nagata et al. 1990; Okuda et al. 1990; Glass et al. 1990). Apparently, each object is composed of a powerful star(s) surrounded by dust.

Some have suggested that these objects are protostars, or at least not normal giants or supergiants (Okuda et al. 1990; Nagata et al. 1990; Glass et al. 1990); however, protostars would be much younger than the other stars identified in the cluster. Could they be OH/IR stars? Nagata et al. (1990) make strong arguments against this hypothesis, the strongest being that the stars do not have OH masers (Habing et al. 1983; Winnberg et al. 1985; Sjouwerman 1998). In addition, OH/IR stars (1) have deep water and CO absorption bands in their near-infrared spectra, (2) are less luminous than the QPMs, (3) are warmer than the QPMs, and (4) are much older than the QPMs, assuming that they are coeval with other cluster stars. Could they be red supergiant "monsters," i.e., VY CMa? Such stars usually have SiO or water masers and deep water absorption features in the near-infrared. Could they be embedded OB stars? Again, this proposition has the same problem as the idea that they are protostars, i.e., such massive stars should have finished
contracting and cleared away their circumstellar environment in much less than 1 Myr (Stahler 1994).

We suggest that these objects are dusty, late-type, WC stars (DWCLs; cf. Abbott & Conti 1987; Williams et al. 1987; Cohen 1995; FMM96). DWCL stars represent a short-lived phase of evolution when the coolest WC types (WC8 and WC9) tend to form dust shells. Williams et al. (1987) found that 19/27 of the WC8 and WC9 stars they studied have significant circumstellar dust emission that can be fitted by blackbodies with temperatures of 780 to 1650 K (cf. WR 112 and WR 118 in Fig. 5).

To test this hypothesis, we have calculated apparent $K$-band magnitudes that various Galactic WC9 stars would have if they were in the Quintuplet. Despite their common luminosities of $\approx 10^5 L_\odot$, we find that $m_K$ would span a very large range, $\approx 3$ (WR 112) to 12 (WR 92). This is due to the different amounts of thermal emission from circumstellar dust around each star. The QPMs have apparent magnitudes in this range, $m_K \approx 6-9$. Of course, the range for DWCLs is so large that this coincidence simply provides a consistency check, not a proof.

As another test of our hypothesis, we obtained $J$-band spectra of the QPMs so that the classical emission-line spectra might be seen. All known DWCLs begin showing the expected WCL emission-line spectrum in the $J$ band. We found no evidence for emission lines in the $J$-band spectra of these stars. Instead, we observed that the flux is still decreasing strongly with decreasing wavelength, as might be expected on the Wien side of a blackbody distribution. Although this disagrees with the spectral energy distributions of all known DWCLs, note that such stars have all been found in surveys detecting their emission-line spectra. In other words, perhaps there are DWCLs that are completely enshrouded, i.e., their emission-line spectrum is not observable.

The nature of these stars is important for determining the WC/WN ratio in the cluster, a number that provides a crucial test of stellar evolution models (cf. Meynet 1995). If they are DWCLs, then they are dustier than any others, which raises the question: Is there something special about the Galactic center environment, such as its metallicity, which causes the winds of DWCLs to be particularly dusty? If they are not DWCLs, then they represent a new phenomenon. The same logic applies to the mid-infrared sources in the Central cluster (Becklin et al. 1978). One possible avenue for further investigation is to concentrate on what is directly observable, i.e., the outer dust shell. We are pursuing this with high-resolution mid-infrared imaging to measure the sizes of the dust shells as a function of wavelength for the QPMs and template DWCLs.

3.4. Luminous Blue Variables

Luminous blue variables (LBVs; Conti 1984) are rare stars in a presumably short phase of evolution between the main sequence and the Wolf-Rayet (W-R) phase. They number about a half-dozen in the Galaxy and an equal number in the Magellanic Clouds. Given the similarities of the Central cluster to the Quintuplet cluster, it is perhaps no coincidence that both contain LBVs or stars with LBV-like spectra (Tamblyn et al. 1996). FMM95 first identified the Pistol star (134) as an LBV candidate for its location in the H-R diagram, near-infrared spectrum, and spatial proximity to the Pistol Nebula. They also suggested that the star ejected the gas now seen in the surrounding Pistol Nebula. Figer et al. (1998b) presented further near-infrared spectroscopy and photometry and applied wind-atmosphere and stellar evolution models to argue that the star is truly in an LBV stage.

Another cluster star, 362, appears to be luminous, hot, and photometrically variable. It brightened by +0.75 in the
K band while becoming redder by +0.34 mag in $H-K$ between the time when the two data sets were taken. The coincidence of the star becoming redder while also becoming brighter could be explained if it has a cool Mira-type companion. It is also possible that the star was moving to the red in the H-R diagram, as LBVs often do when entering an eruptive stage. We favor the latter interpretation based upon our K-band spectrum (Fig. 7a), which lacks CO absorption features expected from a Mira companion; the spectrum was obtained shortly after the star had brightened, so it should be a fair representation of the spectral energy distribution when the star was brighter. Note that such a large change in $H-K$ is equivalent to a change in effective temperature from $\geq 30,000$ to $\sim 3000$ K for normal stars. Although this range in temperature is rather large, it could be explained by the errors in the photometry. We assume that the fainter photometry is a better representation of the flux emitted by a hot photosphere, so we use it to estimate the luminosity assuming bolometric correction at $K$, $BC_K = -1.5$, the “average” for the LBVs discussed in Blum, DePoy, & Sellgren (1995a).

3.5. Two Nearby Stars

We obtained K-band spectra and photometry for two stars within 5' (12.5 pc projected) of the Quintuplet, which we suspect of being very young (Fig. 10). The stars are N21 and N42 in the list of Nagata et al. (1993) and were selected because they fall to the red side of the reddening vector in a color-color plot, i.e., they are intrinsically red. We expected that they might be similar to the Quintuplet-proper members. Integrating their spectral energy distributions gives $L \gtrsim 10^4 L_\odot$.

The two stars have nearly featureless spectra, except, perhaps, for emission at 2.06 $\mu$m; this feature could be due to the He I line or incomplete cancellation of atmospheric absorption. We favor the first possibility because the latter usually manifests itself as a combination of absorption and emission features, similar in appearance to P Cygni profiles. N42 might have some weak emission features near 2.08 $\mu$m, which lacks CO absorption. We favor the first possibility because the latter gives $H$ and $L$ photometry are from the 1996 July 4 images. $H$ and $K$ photometry are from the 1994 July 20 images. Zero-point magnitudes were determined by observing standard stars for the $J$, $H$, $K_1$, and $L$ photometry. The zero-point magnitudes for the $H_2$ and $K_2$ photometry were set by minimizing $\Delta H$ and $\Delta K$. $K^*$ photometry has been converted to $K$ using the relation in Wainscoat & Cowie 1992. There has been no conversion between nbL and $L$. We assess an error of 0.2 mag for all photometry.
TABLE 3
LUMINOSITY AND IONIZING FLUX ESTIMATES

| ID Number | Spectral Type | log \((L/L_\odot)_\text{Lycb}\) | \(N_{\text{type}}\) | Reference |
|-----------|---------------|-------------------------------|-----------------|-----------|
| 76        | WC9           | 5.75                          | 49.3            | 1         |
| 134       | LB V          | ≥ 6.61                        | < 41.5          | 2         |
| 151       | WC8           | 6.15                          | 49.7            | 1         |
| 157       | < B0 I        | 5.67                          | 48.5            | 3         |
| 192       | M Ia          | 4.90                          | ...             | ...       |
| 211       | DWCL?         | 4.84                          | 48.7            | 4         |
| 231       | DWCL?         | 5.23                          | 48.7            | 4         |
| 235       | < WC8         | 6.49                          | 50.2            | 1         |
| 240       | WN9/Ofpe      | 6.66                          | 50.3            | 5         |
| 241       | WN9/Ofpe      | 6.66                          | 50.3            | 5         |
| 243       | DWCL?         | 4.81                          | 48.7            | 4         |
| 250       | < B0 I        | 6.08                          | 48.5            | 3         |
| 251       | DWCL?         | 4.61                          | ...             | ...       |
| 256       | WN9           | 6.01                          | 49.5            | 1         |
| 257       | B0 I          | ...                           | 48.5            | 3         |
| 258       | DWCL?         | 4.45                          | 48.7            | 4         |
| 269       | OB I          | 5.54                          | 48.5            | 6         |
| 270N      | late          | ...                           | ...             | ...       |
| 270S      | OB I          | ...                           | 48.5            | 6         |
| 274       | WN9           | 6.00                          | 49.5            | 1         |
| 276       | B1 I–B3 I     | 5.48                          | 46.2            | 3         |
| 278       | OB I          | ...                           | 48.5            | 6         |
| 301       | < B0 I        | 5.56                          | 48.5            | 3         |
| 307       | B1.5 Ia       | 6.07                          | 46.3            | 3         |
| 309       | < WC8         | 5.72                          | 49.4            | 1         |
| 311       | B1 I–B3 I     | 5.36                          | 46.2            | 3         |
| 320       | WN9           | 5.97                          | 49.5            | 1         |
| 321       | B1 I–B3 I     | 5.97                          | 49.5            | 1         |
| 344       | B1 I–B3 I     | 5.30                          | 46.2            | 3         |
| 345E      | WN6           | 5.68                          | 49.4            | 1         |
| 358       | B1 I–B3 I     | 5.70                          | 46.2            | 3         |
| 362       | OB I/LB Vc    | 6.44                          | 48.5            | 6         |
| 381       | OB I          | 5.86                          | 48.5            | 6         |
| 406       | B1 I–B3 I     | 5.42                          | 46.2            | 3         |

Note.—Spectral types, luminosities, and ionizing fluxes for the target stars. The total of the luminosities is \(\log \left(\frac{L}{L_\odot}\right)\) = 7.50, or 7.36 without the two LBV stars (134 and 362). The total ionizing flux is \(N_{\text{type}} = 50.9 \text{ s}^{-1}\).

\* The luminosities were estimated assuming \(d = 8000 \text{ pc}\) and \(A_K = 3.28\).

We assume BC\(_g\)s of \(-2.0\) (OB supergiants), \(-3.3\) (WC stars), \(-2.9\) (WN and WN/Ope stars), \(-3.2\) (353E; Crowther & Smith 1996), and \(-1.5\) (LBVs; Figer et al. 1998b). For the DWCLs, we integrated under the blackbody fits to the dereddened energy distributions. We assume \(A_K = 2.7\) for the QPMs (see text).

\* Ionizing fluxes have been taken directly from the references, except for the W-R stars, where the following prescription has been used. \(N_{\text{type}} = q_{0,M} L / (\sigma T^4)\), where \(q_{0,M}\) is taken from the reference and is estimated as \(24.9\) for 353E, 23.6 for the WN stars, 24.2 for the WC8 and WC9 stars, and 24.8 for the < WC8 stars; we assume temperatures of 55,000 K for 353E, 30,000 K for the WN stars, 42,000 K for the WC9 star, 48,500 K for the WC8 star, and 55,000 K for the < WC8 stars.

\* We assume BC\(_g\) of 2.60 for an average M supergiant.

\* This estimate assumes the fainter photometry of 1994 July 20 and \(A_K = -1.5\), typical of LBVs and very conservative for stars hotter than 20,000 K.

References.—(1) Crowther & Smith 1996; (2) Figer et al. 1998b; (3) Panagia 1973; (4) Blum, Sellgren, & DePoy 1995b; (5) Najarro et al. 1997; (6) Vacca, Garmany, & Shull 1996.

The energy distributions and emission lines favor the possibility that these are hot stars embedded in dust. It is unclear whether these stars were formed in the same or related star formation events. They might be outlying members of the Quintuplet cluster, but it is difficult to determine without having velocities or ages for the stars.

4. CLUSTER PROPERTIES

In this section, we sum the individual contributions to the cluster properties in order to allow a comparison to other massive clusters and to determine whether the cluster is heating and ionizing nearby clouds and H II regions. For most parameters we give the observed quantities, as well as the implied values, assuming a Salpeter IMF (Salpeter 1955) and a particular lower mass cutoff as discussed below. Most of the estimates depend upon luminosities of the individual stars, so we start by estimating the extinction and distance.

4.1. Extinction

Figer et al. (1998b) reviewed extinction estimates to the cluster for their study of the Pistol star, estimating \(A_K = 3.28\). The estimate represents an average value inferred from color excesses of the stars in Table 1. Table 4 tabulates apparent colors and color excesses for the hot stars identified in the cluster. We consider two sample groups, the “B1 I–B3 I” stars \((N = 5)\), for which the spectral classifications are the most precise in the sample, and the OB I stars \((N = 9)\); the latter includes the former. Although the OB I stars potentially span a larger range in subtype, i.e., O3–B9, they span a very narrow range in colors (cf. Koornneef 1983), so we assume that all such stars have similar colors.

We use \(A_K = 3.28 ± 0.5\) \((A_V = 29 ± 5)\) throughout this paper, unless otherwise noted, where the error is the quadrature sum of the standard deviation of \((H−K)\) for the full sample of OB supergiant stars in the cluster and the photometric errors. The variation in \((H−K)\) for these stars is due to differences in the apparent colors of the stars, i.e., it is not due to inaccurate photometry or confusion. This can be seen in K-band spectra that show that \(A_K = 3.28\) would overestimate the reddening to some of the stars, i.e., their dereddened energy distributions would be greater than that of an infinite temperature blackbody. We take this to indicate that there is some differential extinction across the field and that an extinction value for each star will eventually have to be individually computed; however, the Quintuplet-proper members are probably intrinsically very red. (We cannot estimate the true error in our estimate because it is dominated by systematic effects in the extinction law.)

4.2. Distance

We argue that the cluster is at the distance of the Galactic center \((d_H = 8000 \text{ pc}; \text{Reid} 1993)\) for four reasons.

First, \(V_{\text{LOS}}\approx 130 \text{ km s}^{-1}\) for the cluster stars in every case where it has been measured (Figer 1995); this is also true for gas in the Pistol Nebula (Yusef-Zadeh, Morris, & van Gorkom 1989; Figer 1995; Lang, Goss, & Wood 1997).

Such a high velocity is unlikely for objects along the line of sight to the Galactic center, and a value of this magnitude is expected for an object with an orbital radius equal to the projected radius of the Quintuplet from the Galactic center, i.e., \(v_{\text{orbital}} = (GM/R)^{1/2} \approx 150 \text{ km s}^{-1}\,) where \(M = 10^{6.2}\) \(M_\odot\) is the enclosed mass inside a 30 pc orbit (Sellgren 1989).

Second, the Quintuplet cluster appears to be ionizing the nearby “25 km s\(^{-1}\) cloud” \((M = 0.20 \text{ pc} 0.33; \text{Lasenby},\)
Fig. 5.—$K$-band spectra of W-R stars in the Galaxy obtained with the same instrument and setup as was used to obtain the target spectra in this paper ($R \approx 525$). The identification numbers are taken from van der Hucht et al. (1981). WC stars are shown in the left panels, and WN stars are shown in the right panels. Likely emission-line identifications are indicated by tick marks.

### TABLE 4

| Spectral Type | 1996 Jul 4 $(J-H)$ | 1994 Jun 20 $(H-K)$ | 1996 Jul 4 $(H-K)$ | 1996 Jul 4 $(K-L)^c$ |
|---------------|-------------------|-------------------|-------------------|-------------------|
| (B1 I–B3 I)$_{\text{observed}}$ | 3.21 | 1.83 | 1.80 | 1.18 |
| (B1 I–B3 I)$_{\text{intrinsic}}^b$ | $-0.04$ | $-0.03$ | $-0.03$ | $-0.07$ |
| $E$(B1 I–B3 I) | 3.25 | 1.86 | 1.83 | 1.25 |
| $A_K^a$ | $3.40 \pm 0.60$ | $3.30 \pm 0.18$ | $3.26 \pm 0.34$ | $3.01 \pm 0.50$ |
| OB I$_{\text{observed}}$ | 3.30 | 1.78 | 1.89 | 1.23 |
| OB I$_{\text{intrinsic}}^b$ | $-0.07$ | $-0.04$ | $-0.04$ | $-0.07$ |
| $E$(OB I) | 3.37 | 1.82 | 1.93 | 1.30 |
| $A_K^a$ | $3.53 \pm 1.21$ | $3.23 \pm 0.38$ | $3.43 \pm 1.12$ | $3.13 \pm 1.04$ |

Note.—The extinction has been inferred from measured color excesses for the early B supergiants alone and for the wider, and inclusive, sample of all OB supergiants. The B1 I–B3 I stars are 276, 311, 344, 358, and 406. The OB I sample contains all of the B supergiants listed above and 269, 278, 362, and 381. The dates indicate when the measurements were made; note that there are two determinations of $H-K$ taken from two different nights. The unweighted average of all estimates is $A_K = 3.28 \pm 0.16$. The weighted average is $3.27 \pm 0.06$. Note that the quoted statistical errors are likely to be less than systematic errors due to uncertainty in the zero points and the extinction law.

$a$ There has been no conversion between $nbl$ and $L$.

$b$ Values were taken from Koornneef 1983.

$c$ Assumes the extinction law of Rieke, Rieke, & Paul 1989, i.e., $A_J/A_K = 2.73$, $A_H/A_K = 1.56$, and $A_L/A_K = 0.59$. 
Lasenby, & Yusef-Zadeh 1989; Serabyn & Güsten 1991), thus creating the Sickle (Yusef-Zadeh & Morris 1987; Figer 1996; Lang et al. 1997). The particularly large line widths associated with the molecular cloud are consistent with a location within the central molecular zone of the GC (Serabyn & Morris 1994).

Third, the inferred extinction (see above), interstellar polarization, and silicate absorption produced by the intervening interstellar medium to the cluster are consistent with a location at the GC (Okuda et al. 1990).

Finally, components of the CO absorption band head at 4.66 μm in the QPMs' spectra have been attributed to the 250 pc ring (Okuda et al. 1990) due to their velocity shifts.

4.3. Luminosity

The total cluster luminosity can be estimated by summing the individual luminosities of the identified stars. This will provide a lower limit because the cluster probably contains many unseen lower mass members; however, the total cluster luminosity should be dominated by massive stars for a reasonable IMF. We assumed a distance, extinction, and bolometric correction for each star and tabulated the results in Table 3. It is important to note that this estimate assumes that the cluster is coeval and that the present-day masses are well determined by the spectroscopic analysis above.

In order to estimate luminosities, we estimate the bolometric correction at $K$, $BC_K = M_{bol} - M_K$. For the Ofpe/ WN9 stars, we assume $BC_K = -2.9$ (Najarro et al. 1997). We assume $BC_K = -3.3$ for the WC stars and $BC_K = -2.9$ for the WN stars (Crowther & Smith 1996). We integrate the infrared flux for the DWCL stars. For the OB supergiant stars, we assume $BC_K = -2.0$. This is somewhat conservative compared to $BC_K = -2.4$, which is found by subtracting $V-K$ (Koornneef 1983) from $BC_V$ for O9 I stars (Vacca, Garmany, & Shull 1996); however, it allows for the fact that some of the OB supergiant stars will be later than late O type. For the LBVs, we assume $BC_K = -1.5$, according to the analysis of the Pistol star by Figer et al. (1998b).
Fig. 7.—K-band spectra of OB supergiants in the Quintuplet. In cases where two spectra are shown, the upper spectrum was taken on the earlier date. A curve for a hot blackbody has been overplotted for comparison. The <B0 I stars have nearly featureless spectra that can only be matched to spectra of stars earlier than B0 I. The OB I stars have an ambiguous classification, which shows a hint of absorption in the 2.112 \mu m He I line and the 2.166 \mu m H I line with a small amount of excess emission in the 2.058 \mu m He I line in some cases. The dereddened spectra are steeper than the blackbody curve in some cases, i.e., 270S. Evidently, \( A_k \) is too high for this star. Note the lack of CO absorption features, i.e., at 2.294 \mu m, in the spectrum for 362 (see text). See caption for Fig. 6a for more.

Fig. 8.—K-band spectra of early B supergiants in the Quintuplet. In cases where two spectra are shown, the upper spectrum was taken on the earlier date. A curve for a hot blackbody has been overplotted for comparison. Features at 2.312 and 2.370 \mu m are due to imperfect atmospheric correction. The spectra for 311 and 344 have low signal to noise. The 1996 August 20, spectrum of 311 reveals a late-type companion as seen in the CO absorption features longward of 2.29 \mu m. See caption for Fig. 6a for more.

Fig. 9.—(a) Dereddened spectral energy distribution of 243 (1 in MGM94). We assume \( A_k = 2.7 \) because this value gives the best fit between the observations and the blackbodies. A best-fit blackbody curve has been overplotted here and in (b)–(e). (b) Dereddened spectral energy distribution of 231 (2 in MGM94). (c) Dereddened spectral energy distribution of 211 (3 in MGM94). (d) Dereddened spectral energy distribution of 251 (4 in MGM94). (e) Dereddened spectral energy distribution of 258 (9 in MGM94).
The total cluster luminosity is $10^{7.5} L_\odot$, counting all the stars in Table 3 and using the lower luminosity limit for the Pistol star. Two of the most luminous stars in the cluster are LBVs, stars that span a very large range in BC; but even without these two stars, we find $L_{\text{cluster}} = 10^{7.3} L_\odot$. Either value suggests that the Quintuplet cluster is responsible for heating M0.20–0.033, which emits $10^7 L_\odot$ of radiation at infrared wavelengths (Morris, Davidson, & Werner 1995).

4.4. Mass

The total cluster mass cannot be directly estimated because the mass function has not been measured. The following analysis makes the assumption that the cluster has an IMF slope that is nearly Salpeter (Salpeter 1955). Note that measured IMF slopes vary considerably about the Salpeter value (Scalo 1998).

We estimate the total cluster mass by counting the number of stars with initial masses between an assumed upper mass cutoff of 120 $M_\odot$ and the lowest initial mass inferred from the list of stars identified in Table 1, $\approx 20 M_\odot$. Assuming 30 stars in this mass range, we calculate $M_{\text{cluster}} \approx 10^{4.2} M_\odot$ for $m_{\text{lower}} = 0.1 M_\odot$ and $10^{3.8} M_\odot$ for $m_{\text{lower}} = 1 M_\odot$.

We can compare this value to the mass required to ensure that the cluster is bound against tidal disruption. Assuming a circular orbit with a velocity equal to the line-of-sight velocity (130 km s$^{-1}$; Figer 1995) and an orbital radius equal to the projected distance from the GC, we find an orbital time of $\approx 1.5$ Myr. The enclosed mass at this radius is $\approx 10^{8.2} M_\odot$ (Sellgren 1989). The condition for a star to be tidally bound at radius $r_{\text{cluster}}$ is $M_{\text{total}} \gtrsim 2 \times m_{\text{stellar}} \times (r_{\text{cluster}}/30 \text{ pc})^2 = 10^{4.1} M_\odot$, where $r_{\text{cluster}}$ is the average distance of the stars in the table from the center of the cluster and is $\approx 1$ pc. This value is on the same order as the values above, which suggests that the cluster is marginally bound against tidal disruption, at best.

4.5. Age

To estimate a single cluster age, we must assume that the cluster members in Table 1 are coeval. The notion of coevality is ambiguous when contraction timescales widely range, such as is the case when comparing high-mass stars to low-mass stars. We are not subject to this problem for the current analysis because we are concerned only with the massive stars, which all have very short contraction times (Stahler 1994).

Model isochrones from the Geneva models (Meynet et al. 1994) are shown in Figure 11 for twice solar metallicity and the “2 $\times$ M” models. Data for the B supergiants in Table 1 are well fitted by cool blackbody curves. See caption for Fig. 6a for more.

Fig. 11.—Model isochrones from the Geneva models for $Z = 0.04$ with “2 $\times$ ” mass loss. Isochrones begin at 1 Myr and are spaced by 1 Myr. Data for early B supergiants in the Quintuplet cluster are overplotted. The error in temperature covers the range for B1–B3 I stars. The error in luminosity is dominated by errors in determining the extinction. Assuming that the upper data points are influenced by confusion or binarity, we find a cluster age $\approx 4$ Myr.
have been overplotted. The stars have been given the same temperatures in light of their similar classifications, although note that the uncertainty in the spectral classifications is not represented in the error bar. Using lower metallicity or lower mass-loss rates will tend to give a higher age for the cluster, where the extreme value of 6 Myr is given by solar metallicity and the “standard M” models.

The assumption of coevality is roughly consistent with the ages we estimate for the individual stars in Table 1 (Meynet 1995, and references therein). The presence of WC stars requires that the cluster is older than 2.5 Myr. The sole red supergiant requires an age \( \geq 4 \) Myr (assuming \( M_{\text{initial}} = 40 \, M_\odot \), “2 \times M” models, and \( Z = 0.04 \)). The Pistol star requires an age of \( \leq 2.1 \) Myr, according to Figer et al. (1998b). The presence of O I stars requires an age between 2.5 and 4.7 Myr, depending on the mass-loss rates and the metallicity. We adopt an “average” age of 4 Myr for the cluster.

### 4.6. Ionizing Flux

Harris et al. (1994) estimate that the Sickle requires a Lyman continuum flux of \( Q_{\text{Sickle}} \approx 10^{50.5} \) s\(^{-1}\), and, according to Yusef-Zadeh et al. (1989), the Pistol requires \( Q_{\text{Pistol}} \approx 10^{48.6} \) s\(^{-1}\). Timmermann et al. (1996) use the radio flux at 32 GHz to estimate that the Quintuplet produces \( Q_{\text{Quin,radio}} \approx 10^{50.2} \eta \) s\(^{-1}\), where \( \eta \) is less than 1 and accounts for dust absorption and deviations from an ionization-bounded region.

### 5. The Quintuplet Cluster in Context

#### 5.1. The Quintuplet Cluster Compared to Other Massive Clusters

Table 5 compares the Quintuplet cluster and other massive clusters in mass, size, density, age, luminosity, and Lyman continuum flux. The total mass of observed stars, “M1,” is subject to observational effects because of the

| Cluster               | log \( M_1 \) (\( M_\odot \)) | log \( M_2 \) (\( M_\odot \)) | Radius (pc) | log \( \rho_1 \) (\( M_\odot \) pc\(^{-3}\)) | log \( \rho_2 \) (\( M_\odot \) pc\(^{-3}\)) | Age (Myr) | log \( L \) (\( L_\odot \)) | log \( Q \) (s\(^{-1}\)) |
|----------------------|-----------------------------|-----------------------------|--------------|--------------------------------|--------------------------------|----------|-----------------|-----------------|
| Quintuplet           | 3.0                         | 3.8                         | 1.0          | 2.4                           | 3.2                           | 3–6      | 7.5             | 50.9            |
| Arches*              | 3.7                         | 4.3                         | 0.19         | 5.2                           | 5.8                           | 1–2      | 8.0             | 51.0            |
| Center               | 3.0                         | 4.0                         | 0.23         | 4.6                           | 5.6                           | 3–7      | 7.3             | 50.5            |
| NGC 3603             | 3.1                         | 3.7                         | 0.23         | 4.3                           | 5.0                           | 2.5      | 7.3             | 51.1            |
| Trapezium            | 1.5                         | 1.5                         | 0.05         | 4.7                           | 5.0                           | 0.3      | 5.3             | 48.9            |
| R136               | 3.4                         | 4.5                         | 1.6          | 2.2                           | 3.3                           | <1–2     | >7.6            | 51.9            |
| Small globular (M5)  | 4.8                         | 4.8                         | 4.0          | 2.3                           | 3.1                           | ...      | ...             | ...             |
| Typical globular (M13)| 5.5                         | 3.9                         | ...          | 3.1                           | ...                           | ...      | ...             | ...             |
| Large globular (M22) | 6.8                         | 3.2                         | ...          | 4.7                           | ...                           | ...      | ...             | ...             |
| NGC 1705-1           | 4.9                         | 4.9                         | 0.9          | 4.4                           | 10–20                        | ...      | ...             | ...             |
| NGC 1569-A           | 5.5                         | 1.9                         | ...          | 4.0                           | 10–20                        | ...      | ...             | ...             |

**Note:** — \( M_1 \) is the total cluster mass in observed stars. \( M_2 \) is the total cluster mass in all stars extrapolated down to a lower mass cutoff of \( 1 \, M_\odot \), assuming a Salpeter IMF slope and an upper mass cutoff of \( 120 \, M_\odot \) (unless otherwise noted); note that the total cluster mass would be 2.5 times greater if the lower mass cutoff is \( 0.1 \, M_\odot \). Radius gives the average projected separation from the centroid position. \( \rho_1 \) is \( M_1 \) divided by the volume. \( \rho_2 \) is \( M_2 \) divided by the volume. In either case, this is probably closer to the central density than the average density because the mass is for the whole cluster, whereas the radius is the average projected radius. Age is the assumed age for the cluster. Luminosity gives the total measured luminosity for observed stars. \( Q \) is the estimated Lyman continuum flux emitted by the cluster.

* Serabyn, Shupe, & Figer 1998.
  * Drissen et al. 1995. The mass, \( M_2 \), has been estimated by assuming that a total \( 10^{5.5} \) stars have been formed. The age spans a range covering an initial starburst, followed by an exponential decay in the star formation rate.
  * Drissen et al. 1995. \( M_1 \) was estimated by assuming that the 37 stars in Table 3 of Moffat, Drissen, & Shara 1994 have \( 15 < M_{\text{initial}} < 120 \, M_\odot \). The size is the average projected radius for the stars in Table 3. The age is estimated by assuming that there are true helium-burning Wolf-Rayet stars in the cluster. See Eisenhauer et al. 1998 for an alternate interpretation. The luminosity has been estimated by assuming that the stars in Table 3 have an average luminosity of \( 10^{5.7} \, L_\odot \).
  * Drissen & Staufier 1994. The radius comes from the region that was probed with deep infrared imaging. \( \rho_2 \) is the stellar number density, i.e., it represents the mass density if the average mass per star is \( 1 \, M_\odot \). This number has been corrected for projection effects, i.e., volume number density = \( 2 \times \) surface number density. \( Q \) is from Kennicutt 1984.
  * Massey & Hunter 1998. \( M_1 \) is a count of the total mass of the 29 stars in Table 3 of Massey & Hunter 1998, using the Chlebowski & Garmany 1991 calibration (\( 56 \, M_\odot < M_{\text{initial}} < 136 \, M_\odot \)). Age corresponds to the young population of high-mass stars. \( Q \) is from Walborn 1991.
  * Allen 1973.
  * Ho & Filippenko 1996. The masses, \( M_2 \), are inferred by measuring velocity dispersions and invoking the virial theorem.
varying distances of the clusters and the extent to which they have been studied. “M2” is supposed to represent the total inferred mass of the cluster; note that our estimates are for an IMF truncated below 1 $M_\odot$. The radius is normally taken as the half-light radius, or average distance from the centroid of the cluster. Because of the slightly different definitions used in the estimates, the values should be taken as a rough indication of compactness; the same caution is obviously applicable to the resultant densities, “$\rho_1$” and “$\rho_2$,” which are simply the mass estimates divided by the volume.

The Quintuplet cluster is most comparable to NGC 3603 in mass and luminosity, but notice that it is much less dense, probably older, and produces less ionizing flux. Perhaps the differences in density and ionizing flux result from the difference in age, that is, the inevitable expansion of an unbound cluster and the natural decrease of ionizing flux with age. The former effect might be amplified in the strong tidal field of the Galactic center. Age might also be the reason for the large number of W-R stars in the Quintuplet cluster (8 to 13) compared to NGC 3603 (3, of the H-rich variety). In fact, the W-R stars in NGC 3603 are probably hydrogen core burning O stars with particularly thick winds, like those found in R136 (Massey & Hunter 1998); such stars are younger than “true,” i.e., He-burning, W-R stars.

5.2. The Quintuplet Cluster and the Central Cluster

The emission-line stars in the central parsec of the Galaxy have been regarded as “exotic” for their spectral characteristics in the K band (Allen, Hyland, & Hillier 1990; Krabbe et al. 1991; Libonate et al. 1995; Krabbe et al. 1995; Blum, Sellgren, & DePoy 1995b; Tamblyn et al. 1996). Although similar stars can be found in the Galaxy and the Large Magellanic cloud, they are rare and the ensemble of stars at the center, as a collection, is remarkable because it contains a concentration of such striking stars.

The Quintuplet cluster contains similar stars, as can be seen in Figure 4 and FMM95. The WC9 stars found in the center (Blum et al. 1995b; Krabbe et al. 1995) have counterparts in the Quintuplet cluster (here and FMM95-2); in fact, IRS 6 in the Galactic center is a particularly dusty WC9. IRS 16NE, which has LBV-like spectral characteristics (Tamblyn et al. 1996), is similar to the Pistol star and 362. Some of the Ofpe/WN9 types in the center (IRS 16 components) are similar to q9, q10 (Geballe et al. 1994; Figer 1995; Cotera et al. 1996), and FMM95-1. IRS 33E, IRS 16NE, and IRS 16NW have spectra similar to the OB supergiant stars in the Quintuplet (Figer 1995; Najarro 1995; Genzel et al. 1996). IRS 7, the red supergiant in the central cluster, is similar to q7 in the Quintuplet (Moneti et al. 1994). Finally, the QPMs share similar spectral energy distributions (Okuda et al. 1990; Becklin et al. 1978) and K-band spectra (Figer 1995) with the very red sources in the Galactic center, cf. IRS 8; both groups of stars may be dusty, late-type, WC stars (DWCLs).

In total, both clusters have approximately 27 supergiant stars and contain roughly equal numbers of massive subtypes; therefore, the total mass in massive identified stars is the same in both clusters, $\approx 10^3 M_\odot$ (see Table 5). The small difference in total mass extrapolated down to $m_{\text{lower}}$ is due to the different techniques used to make this estimate (see notes in Table 5 and Krabbe et al. 1995). The difference in “$\rho_2$” is due to the difference in radius for the two clusters, but this is likely owed to a selection effect. The central cluster has been probed with very high-resolution measure-ments, something that has not been done for the Quintuplet cluster. Indeed, there appears to be a dense clustering of bright stars in the north-south ridge situated between the four westernmost QPMs and 211. Some of those stars have already been identified as being very massive, but more identifications are limited by the spatial resolution of current observations. Further identifications in this stellar concentration would lower the effective radius for massive stars in the cluster. The collective luminosity and Lyman continuum flux for stars in each cluster are similar, where differences might be attributable to modeling.

In summary, the Quintuplet and Central cluster are nearly identical in mass and age. The primary difference seems to be the enigmatic broad helium-line stars in the Central cluster (Krabbe et al. 1991). However, those stars are still evolved massive stars like the ones found in the Quintuplet cluster, and the detailed line profiles in the Central cluster stars are likely due to a small difference in age between stars in the two clusters (Najarro et al. 1997).

5.3. The Quintuplet, Pistol, Sickle Complex

The center of the Quintuplet cluster is situated $\approx 10'$ due north of G0.15$-$0.05 (the Pistol) and a few arcminutes to the southeast of G0.18$-$0.04 (the Sickle) (see Yusef-Zadeh & Morris 1987 for nomenclature). Serabyn & Güsten (1991) argued that the Sickle H $\alpha$ region is the ionized surface of M 0.20 0.033 (the “25 km s$^{-1}$ molecular cloud”). Serabyn & Morris (1994) suggested that free electrons in the Sickle are accelerated by MHD interactions at this interface and that resultant relativistic electrons stream along nearby magnetic field lines, producing the nonthermal radio arcs. FMM95 suggested that the Pistel Nebula was ejected from, and is now partially ionized by, the Pistol star.

The data in this paper are consistent with the hypothesis that the Quintuplet cluster is heating dust in M0.20$-$0.033 and ionizing the gas in the Sickle. M0.20$-$0.033 emits $\approx 10^3 L_\odot$ at far-infrared wavelengths (Morris et al. 1995), consistent with the idea that the Quintuplet cluster and the molecular cloud are physically connected and not just coincident along the line of sight. Note that the large difference in velocities for the cluster and the cloud indicates that the cloud probably did not spawn the cluster.

Lang et al. (1997) presented radio recombination line data of both the Pistol and the Sickle, which shows that the former might be enhanced in helium, whereas the latter has solar helium abundance. Again, this is consistent with the idea that the molecular cloud is a wayward interloper in the region, whereas the Pistol Nebula is composed of ejecta that have been subject to stellar nucleosynthesis. They also showed that ionized gas at the edges of the Sickle has been accelerated to higher velocities than that near the center of the nebula and the molecular gas in the cloud. We interpret this velocity field as indicating an interaction between the strong winds of the Quintuplet stars and the surface of M0.20$-$0.033. This agrees with Simpson et al. (1997), who suggest that the higher velocities come from a “champagne flow” interaction (also see Lang et al. 1997)

A nearby ring of emission at $l, b = (+0.15, -0.14)$ has been detected in mid-infrared data by the Midcourse Space Experiment (MSX); Shipman, Egan, & Price 1996). This ring appears to be associated with the complex, being coincident on its northwest portion with the Sickle (Egan et al. 1998). The cluster is offset from the center of the bubble, but such an offset might be explained by a relative motion of the
Quintuplet cluster and the local interstellar medium (ISM), or to a large-scale density gradient in the medium into which the bubble is expanding. Assuming that winds and radiation pressure from O stars in the cluster have plowed the local ISM into a dust shell, we might expect a bubble expansion timescale of $10^4$ yr ($V_{exp} = 1000$ km s$^{-1}$). Such a timescale is more reasonable for a shell that was swept up by an expanding supernova shock front. Indeed, we expect 1 supernova per 50,000 yr in the cluster, starting at a cluster age of $\approx$4 Myr according to Meynet (1995). A further analysis of this dust ring is under way using Infrared Space Observatory data to investigate the excitation and kinematics (Levine, Morris, & Figer 1999).

5.4. The Quintuplet as a “Super Star Cluster”

Ho & Filippenko (1996, and references therein) argued that we are seeing present-day globular cluster formation in other galaxies. These super star clusters are recognized for their large luminosities, large masses, and compactness. Some have claimed that such clusters are produced in turbulent environments. Table 5 includes the physical characteristics of globular and super star clusters for comparison with the three Galactic center clusters. The Quintuplet cluster, Arches cluster, and the Central cluster are similar to the other objects compared in the table, except for their smaller mass, which suggests that they represent the low-mass end of the distribution of such objects.

If correct, then the GC clusters would be the closest examples of super star clusters. It would also add evidence that such clusters can form in galaxies that are not interacting. This might suggest a unified model for such phenomena. Perhaps super star clusters are formed wherever dense molecular clouds collide, or are strongly shocked, to form dense, massive clusters. Such environments might be found in the early Galaxy and colliding galaxies, but they might also be found in the present-day Galactic center. We speculate that the strength of the shock that provokes the cluster formation is the primary determinant of the cluster mass. In that case, the more violent encounters, such as those which occur in colliding galaxies, are the ones that would naturally produce the most massive clusters.

6. Conclusions

Although many of the parameters derived in this paper rely upon only near-infrared data, we conclude the following. The Quintuplet cluster is extraordinary for its content of massive stars, containing more bona fide Wolf-Rayet stars than any other cluster in the Galaxy. It is the source of ionizing photons for the nearby H$\alpha$ regions, the “Pistol” and the “Sickle.” The types of stars found in the cluster are consistent with a coeval population, and the cluster age is $\approx 4 \pm 1$ Myr, according to stellar evolution models. The total mass in observed stars is $\approx 10^6 M_\odot$, and the inferred mass is $\approx 10^8 M_\odot$ for a Salpeter IMF and a lower mass cutoff in the range of 1 to 0.1 $M_\odot$. The observed mass density in stars is greater than or similar to a few hundred $M_\odot$ pc$^{-3}$, and the inferred density is greater than or similar to a few thousand $M_\odot$ pc$^{-3}$. The cluster is one of three massive clusters in the Galactic center that are similar in many respects to super star clusters found in other galaxies. The current sample is limited to massive stars in various stages of post–main-sequence evolution and their initial masses are difficult to estimate. An accurate determination of the IMF in this cluster must await deeper observations (NICMOS/HST; Figer et al. 1999a), which will reveal main-sequence stars, where the association between infrared flux and initial mass is better known.

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REFERENCES

Abbott, D. C., & Conti, P. S. 1987, ARA&A, 25, 113
Allen, C. W. 1973, Astrophysical Quantities (3d ed. London: Athlone)
Allen, D. A., Hyland, A. R., & Hillier, D. J. 1990, MNRAS, 244, 706
Becklin, E. E., Matthews, K., Neugebauer, G., & Willner, S. P. 1978, ApJ, 219, 121
Blum, R. D., DePoy, D. L., & Sellgren, K. 1995a, ApJ, 441, 603
Blum, R. D., Sellgren, K., & DePoy, D. L. 1995b, ApJ, 440, L17
Chlewbowski, T., & Garmany, C. D. 1991, ApJ, 368, 241
Cohen, M. 1995, ApJS, 100, 415
Conti, P. S. 1984, in IAU Symp. 105, Observational Tests of Stellar Evolution Theory, ed. A. Maeder & A. Renzini (Dordrecht: Reidel), 233
Cotera, A. S., Erickson, E. F., Colgan, S. W. J., Simpson, J. P., Allen, D. A., & Burton, M. G. 1996, ApJ, 461, 750
Crowther, P. A., & Smith, L. J. 1996, A&A, 305, 541
Drissen, L., Moffat, A. F. J., Walborn, N. R., & Shara, M. M. 1995, AJ, 110, 2235
Egan, M. P., Shrijman, R. F., Price, S. D., Carey, S. J., Clark, F. O., & Cohen, M. 1998, ApJ, 494, L199
Eisenhauer, F., Quirrenbach, A., Zinnecker, H., & Genzel, R. 1998, ApJ, 499, 278
Elia, J. H., Frogel, J. A., Matthews, K., & Neubauer, G. 1982, AJ, 87, 1029
Figer, D. F. 1995, Ph.D. thesis, Univ. California, Los Angeles
Figer, D. F., McLean, I. S., & Morris, M. 1995, ApJ, 447, L29 (FMM95)
Figer, D. F., McLean, I. S., & Najarro, F. 1998a, in IAU Symp. 184, The Central Regions of the Galaxy and Galaxies (Dordrecht: Kluwer), 25
Figer, D. F., McLean, I. S., & Najarro, F. 1997, ApJ, 486, 420
Figer, D. F., Morris, M., & McLean, I. S. 1996, in ASP Conf. Ser. 102, The Galactic Center, 4th ESO/CTIO Workshop, ed. R. Gredel (San Francisco: ASP), 263 (FMM96)
Figer, D. F., Najarro, F., Morris, M., McLean, I. S., Geballe, T. R., Ghez, A. M., & Langer, N. 1998b, ApJ, 506, 384
Figer, D. F., et al. 1999a, in preparation
Figer, D. F., Rich, R. M., Morris, M., McLean, I. S., Serabyn, E., Puetter, R., & Yahil, A. 1999b, in preparation
Geballe, T. R., Genzel, R., Krabbe, A., Krenz, T., & Lutz, D. 1994, in Infrared Astronomy with Arrays, ed. I. S. McLean (Dordrecht: Kluwer), 73
Genzel, R., Thatte, N., Krabbe, A., Kroker, H., & Taconi-Garman, L. E. 1996, ApJ, 472, 157
Glass, I. S., Catchpole, R. M., & Whitelock, P. A. 1987, MNRAS, 227, 373
Glass, I. S., Moneti, A., & Moorwood, A. F. M. 1990, MNRAS, 242, 55P
Habing, H. J., Olson, R. M., Winnberg, A., Matthews, H. E., & Baud, V. 1983, A&A, 120, 230
Hanson, M. M., Conti, P. S., & Rieke, M. J. 1996, ApJS, 107, 281
Harris, A. I., Townes, C. H., & Geballe, T. R. 1994, in The Nuclei of Normal Galaxies: Lessons from the Galactic Center, ed. R. Genzel & A. I. Harris (Dordrecht: Kluwer), 223
Ho, L. C., & Filippenko, A. V. 1996, ApJ, 472, 600
Kennicutt, R. C. 1984, ApJ, 287, 116
Koornneef, J. 1983, A&A, 128, 84
Krabbe, A., Genzel, R., Drapatz, S., & Rotaciuc, V. 1991, ApJ, 382, L17
Krabbe, A., et al. 1995, ApJ, 447, L95
Lang, C. C., Goss, W. M., & Wood, D. O. S. 1997, ApJ, 474, 275
Lasenby, J., Lasenby, A. N., & Vailes-Zadeh, F. 1989, ApJ, 343, 177
Levine, D., Morris, M., & Figer, D. F. 1999, in Proc. ESA Special Publication Ser. 427, The Universe as Seen by ISO (Noordwijk: ESA), in press
Libonate, S., Pipher, J. L., Forrest, W. J., & Ashby, M. L. N. 1995, ApJ, 439, 202
Massey, P., & Hunter, D. A. 1998, ApJ, 493, 180
McCaughrean, M. J., & Stauffer, J. R. 1994, AJ, 108, 1382
McLean, I. S., et al. 1993, in Infrared Detectors and Instrumentation, ed. A. Fowler (Bellingham: SPIE), 513
________. 1994, in Instrumentation in Astronomy VIII, ed. D. Crawford (Bellingham: SPIE), 457
Meynet, G. 1995, A&A, 298, 767
Meynet, G., Maeder, A., Schaller, G., Schaerer, D., & Charbonnel, C. 1994, A&A, 103, 97
Moffat, A. F. J., Drissen, L., & Shara, M. M. 1994, ApJ, 436, 183
Moneti, A., Glass, I. S., & Moorwood, A. F. M. 1994, MNRAS, 268, 194
Morris, M., Davidson, J. A., & Werner, M. W. 1995, in ASP Conf. Ser. 73, Airborne Astronomy Symposium on the Galactic Ecosystem, ed. M. R. Haas, J. A. Davidson, & E. F. Erickson (San Francisco: ASP), 477
Nagata, T., Kobayashi, N., & Sato, S. 1994, ApJ, 423, L113
Nagata, T., Woodward, C. E., Shure, M., & Kobayashi, N. 1995, ApJ, 109, 1676
Nagata, T., Woodward, C. E., Shure, M., Pipher, J. L., & Okuda, H. 1990, ApJ, 351, 83
Najarro, F. 1995, Ph.D. thesis, Ludwig-Maximilian Univ.
Najarro, F., Krabbe, A., Genzel, R., Lutz, D., Kudritzki, R. P., & Hillier, D. J. 1997, A&A, 325, 700
Okuda, H., et al. 1990, ApJ, 351, 89
Panagia, N. 1973, AJ, 78, 929
Reid, M. J. 1993, ARA&A, 31, 345
Rieke, G. H., Rieke, M. J., & Paul, A. E. 1989, ApJ, 336, 752
Salpeter, E. E. 1955, ApJ, 121, 161
Scalo, J. 1998, in ASP Conf. Ser. 142, The Stellar Initial Mass Function (38th Herstmonceux Conf.), ed. G. Gilmore & D. Howell (San Francisco: ASP), 201
Sellgren, K. 1989, in IAU Symp. 136, The Center of the Galaxy, ed. M. Morris (Dordrecht: Kluwer), 477
Serabyn, E., & Güsten, R. 1991, A&A, 242, 376
Serabyn, E., & Morris, M. 1994, ApJ, 424, L91
Serabyn, E., Shupe, D., & Figer, D. F. 1998, Nature, 394, 448
Shipman, R. F., Égan, M. P., & Price, S. D. 1996, BAAS, 189, 61.04
Simpson, J. P., Colgan, S. W. J., Cotera, A. S., Erickson, E. F., Haas, M. R., Morris, M., & Rubin, R. H. 1997, ApJ, 487, 689
Sjouwerman, L. O., Van Langevelde, H. J., Winnberg, A., & Habing, H. J. 1998, A&AS, 128, 35
Stahler, S. W. 1994, PASP, 106, 337
Tamblyn, P., Rieke, G. H., Hanson, M. M., Close, L. M., McCarthy, D. W., Jr., & Rieke, M. J. 1996, ApJ, 456, 206
Timmermann, R., Genzel, R., Poglitsch, A., Lutz, D., Madden, S. C., Nikola, T., Geis, N., & Townes, C. H. 1996, ApJ, 466, 242
Vacca, W. D., Garmany, C. D., & Shull, J. M. 1996, ApJ, 460, 914
van der Hucht, K. A., Conti, P. S., Lundström, I., & Stenholm, B. 1981, Space Sci. Rev., 28, 227
Wainscoat, R. J., & Cowie, L. L. 1992, AJ, 103, 332
Walborn, N. R. 1991, in IAU Symp. 148, The Magellanic Clouds, ed. R. Haynes & D. Milne (Dordrecht: Kluwer), 145
Williams, P. M., van der Hucht, K. A., & Thé, P. S. 1987, A&A, 182, 91
Winneweg, A., Baud, B., Matthews, H. E., Habing, H. J., & Olnon, F. M. 1965, ApJ, 291, L45
Yusef-Zadeh, F., & Morris, M. 1987, AJ, 94, 1178
Yusef-Zadeh, F., Morris, M., & van Gorkom, J. H. 1989, in IAU Symp. 136, The Center of the Galaxy, ed. M. Morris (Dordrecht: Kluwer), 275