NGC 2362: The Terminus of Star Formation

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Abstract. NGC 2362 is a richly populated Galactic cluster, devoid of natal molecular gas and dust. The cluster represents the final product of the star forming process and hosts an unobscured and near-complete initial mass function. NGC 2362 is dominated by the O9 Ib multiple star, \( \tau \) CMa, as well as several dozen unevolved B-type stars. Distributed throughout the cluster are several hundred suspected intermediate and low-mass pre-main sequence members. Various post-main sequence evolutionary models have been used to infer an age of \( \sim 5 \) Myr for the one evolved member, \( \tau \) CMa. These estimates are in close agreement with the ages derived by fitting pre-main sequence isochrones to the contracting, low-mass stellar population of the cluster. The extremely narrow sequence of stars, which extends more than 9 mag in the optical color-magnitude diagram, suggests that star formation within the cluster occurred rapidly and coevally across the full mass spectrum. Ground-based near infrared and H\( \alpha \) emission surveys of NGC 2362 concluded that most (\( \sim 90\% \)) of the low-mass members have already dissipated their optically-thick, inner (\(< 1 \) AU) circumstellar disks. \textit{Spitzer} IRAC observations of the cluster have confirmed these results, placing an upper limit on the primordial, optically thick disk fraction of the cluster at \( \sim 7\% \pm 2\% \). The presence of circumstellar disks among candidate members of NGC 2362 is also strongly mass-dependent, such that no stars more massive than \( \sim 1.2 \) M\( \odot \) exhibit significant infrared excess shortward of 8 \( \mu \)m. NGC 2362 will likely remain a favored target of ground-based and space-based observations. Its well-defined upper main sequence, large population of low-mass, pre-main sequence stars, and the narrow age spread evident in the color-magnitude diagram ensure its role as a standard model of cluster as well as stellar evolution.

1. Introduction

The young cluster NGC 2362 in Canis Majoris (CMa) is dominated by the 4\textsuperscript{th} mag O9 Ib multiple star, \( \tau \) CMa and several dozen B-type stars (McSwain & Gies 2005), spherically distributed within a volume \( \sim 3 \) pc in radius. Shown in Figure 1 is a 15\arcmin \times 15\arcmin \ Second Palomar Observatory Sky Survey (POSS-II) red image of NGC 2362 obtained from the Digitized Sky Survey. The cluster is free of molecular gas and nebular emission and suffers very little interstellar reddening despite an accepted distance of nearly 1.5 kpc. With an age of \( \sim 5 \) Myr, only \( \tau \) CMa has evolved significantly away from the cluster zero-age main sequence (ZAMS). Although probably relaxed, the evaporation timescale for the cluster is significantly greater than its age, implying that few members have dispersed. In essence, an unobscured and near-complete stellar population remains around \( \tau \) CMa, making NGC 2362 an ideal target for initial mass function (IMF) studies (Moitinho et al. 2001). The rich history of the cluster begins with its discovery by Fr. Giovanni Battista Hodierna in Sicily during the 17\textsuperscript{th} century using a Galilean-type refractor. His observations of nebulous objects which includes NGC 2362 were
published in 1654. With only one member (τ CMa) visible to the unaided eye, the cluster quickly returned to obscurity for over a century before Sir William Herschel noted its presence, entry H VII.17 in his catalog of stellar clusters and nebulae, one of the pre-cursors to Dreyer’s New General Catalog (NGC). Dreyer’s notes within the original NGC summarize NGC 2362 as a pretty large, rich cluster centered upon 30 CMa (τ). The compact nature of NGC 2362 is quite striking when viewed on the Palomar Observatory Sky Survey (POSS) plates. The large number of early-type stars form a luminous halo around τ CMa, ∼10' in diameter (Figure 1).

Figure 1. A 15'×15' Second Palomar Observatory Sky Survey (POSS-II) red image of NGC 2362 obtained from the Digitized Sky Survey. τ CMa, the 4th mag O9 Ib star (center), is the most massive cluster member and the only star that has evolved significantly away from the ZAMS. Given the abundance of unevolved B-type members from B1 to B9, the early population of NGC 2362 has often been used to define the upper section of the empirically-derived ZAMS. The pre-main sequence population of NGC 2362 is symmetrically distributed around τ CMa.

Although lacking nebulosity in the immediate cluster vicinity, just over one degree east of NGC 2362 extensive H II emission is apparent on the POSS plates. This emission is part of the giant H II region Sharpless 310, described by Sharpless (1959) as an incomplete ring 8° in diameter. The ionizing sources for this gas are most likely 29 CMa, τ CMa, and the early B-type members of NGC 2362. IRAS images of the
NGC 2362 region reveal that the cluster is located within an evacuated cavity approximately 30′ in diameter. A partial ring of dust emission, most prominent at 60 μm, is evident to the east. The nearby dark nebula, L1667, also believed to be 1.5 kpc distant (Lada & Reid 1978), lies southeast of NGC 2362, near the variable M5 supergiant VY CMa. Tenuous dark clouds appear to follow the contours of H II emission on the POSS plates, perhaps remnants of the molecular cloud complex from which NGC 2362 formed. The OB stellar population of NGC 2362 may have triggered a second generation of star formation within L1660 to the northeast, which hosts the Herbig-Haro object HH 72 (Reipurth & Graham 1988). Shown in Figure 2 is a reproduction of a Schmidt plate from Reipurth & Graham (1988) centered upon L1660 and with the locations of HH 72 and three known Hα emission stars identified. Reipurth & Graham (1988) conclude that L1660 is slowly being eroded away by intense UV radiation from the OB stellar population of NGC 2362 and other nearby massive stars.

2. Cluster Distance and Interstellar Extinction

With an abundance of early-type stars lying on or near the ZAMS, NGC 2362 is seemingly well-suited for precise distance determinations. Distance estimates for the cluster, however, vary significantly in the literature from Humphreys’ (1978) value of 904 pc (for τ CMa) to nearly 2100 pc by Johnson & Morgan (1953). The difficulty in fixing the cluster distance arises from the near vertical slope of the ZAMS for the early-type cluster members in the color-magnitude diagram (CMD). Most recently, Moitinho et al. (2001) used CCD photometry to establish a distance modulus of 11.16 mag for
the cluster by fitting the upper main sequence with the Schmidt-Kaler (1982) ZAMS in the $V$, $U-B$ plane. The $U-B$ color yields the shallowest slope for the B-type stellar sequence, thereby permitting a precise ZAMS fit. From their derived interstellar reddening value of $E_{B-V}=0.1$ mag, and by assuming the standard ratio of total-to-selective absorption, $R_V=3.1$, Moitinho et al. (2001) determined a distance of 1480 pc, which nearly matches that derived by Balona & Laney (1996). Interstellar extinction along the line of sight to NGC 2362 is quite low given the assumed distance of the cluster. All investigations of the cluster are consistent with $E_{B-V} \sim 0.1$ mag and none exhibit evidence for variable extinction across the face of the cluster. Numerous background galaxies are apparent in deep optical images of the field, providing additional circumstantial support for the lack of significant interstellar extinction along the line of sight toward the cluster. Table 1 summarizes the distance and extinction estimates determined by selected investigations of NGC 2362. Also included in the table are the adopted ages and evolutionary models used for the cluster age determinations.

3. The Age of NGC 2362

From the large number of unevolved B-type stars, from B1V to B9V, the age of NGC 2362 has always been inferred to be quite young. Balona & Laney (1996) assigned an age of 5 Myr to NGC 2362 by using the post-main sequence evolutionary models of Meynet et al. (1993) to fit $\tau$ CMa, the only evolved cluster member. The upper main sequence of the cluster is shown in Figure 3, the $(B-V)_0$, $V_0$ (left panel) and the $(V-I)_0$, $V_0$ (right panel) CMDs plotted using photometry and spectral types available in the literature. The sources for the photometric data include Johnson (1950), Johnson & Morgan (1953), Vandenbergh & Hagen (1968), and Blanco et al. (1968). Available spectral types are from numerous sources including Johnson & Morgan (1953), Hiltner, Garrison, & Schild (1969), and Houk & Smith-Moore (1988). The solid line is the Pleiades main sequence from Stauffer (1984), placed at the adopted cluster distance of 1480 pc. The ZAMS derived by Balona & Shobbrook (1984) is shown as a dashed line extending above the Pleiades fit. The ZAMS appears to fit the upper portion of the $(B-V)_0$, $V_0$ CMD well with two exceptions, $\tau$ CMa and HD 57192. As previously stated, $\tau$ CMa is known to be an evolved multiple star, but HD 57192 (B2 V), assuming its published luminosity class, would be overluminous if at the distance of NGC 2362. Kazarovets et al. (1999) identify the star as an eclipsing $\beta$ Lyrae-type binary, which may account for its additional flux assuming identical masses for the two components. Lying $\sim 7^{\prime}$ east of $\tau$ CMa, it is possible that the star is not a cluster member, however, its radial velocity does match that of other members (Evans 1967).

Superposed in Figure 3 are the post-main sequence evolutionary tracks of Schaller et al. (1992) for 40, 15, 5, and 3 $M_\odot$ stars. From the models, the age at which a significant departure from the main sequence first becomes detectable can be estimated for the various stellar masses. If it is assumed that a shift in color of $\sim 0.1$ mag. would be detectable, the ages at which such evolution has occurred are: 4.3 Myr (at 40 $M_\odot$), 6.4 Myr (25 $M_\odot$), and 11.6 Myr (15 $M_\odot$). There is no evidence for evolution away from the ZAMS among the B-type stars, the earliest of which is the B1 dwarf, CD$-24^\circ5180$ (Johnson’s star 30). $\tau$ CMa is seen to lie on the 40 $M_\odot$ track of Schaller et al. (1992), suggesting an age of $\sim 4.1$ Myr if this mass is assumed and its multiple nature ignored. This value agrees well with the post-main sequence age of $\tau$ CMa derived by Moitinho
Figure 3. The $(B - V)_0$, $V_0$ (left) and $(V - I_c)_0$, $V_0$ (right) CMDs for the OB stellar population of NGC 2362. Photometry and spectral types for these stars were obtained from the literature. The solid line rising from the bottom edge of each figure is the Pleiades main sequence from Stauffer (1984). The dashed line extending above the Pleiades fit is the main sequence derived by Balona & Shobbrook (1984). Peeling away from the ZAMS are the post-main sequence evolutionary tracks of Schaller et al. (1992) for 40, 15, 5, and 3 $M_\odot$ stars. The base of each of these evolutionary tracks is labeled with its corresponding mass. On the right side of each panel are the main sequence spectral types at the approximate $V_0$ assuming a distance modulus of 10.85.

et al. (2001) using the models of Girardi et al. (2000). Assuming coevality, significant evolution should not have occurred for any other cluster member given the Schaller et al. (1992) timescales. Alternatively, one could estimate the cluster age using contraction times for the latest B-type stars lying on the ZAMS. Inspection of Figure 3 suggests that above $V_0 \sim 11$, or $M_V \sim -0.2$ (B8), all stars lie in close proximity to the ZAMS. The mean mass for a B8 dwarf is $\sim 3.0$ $M_\odot$ (Andersen 1991), implying a theoretical contraction time of 7.2 Myr (Bernasconi & Maeder 1996). If, however, the B8 stars are still settling onto the ZAMS, and the latest zero-age main sequence stars were of type B5 ($5.0$ $M_\odot$), contraction times of 1.2 Myr follow from the models of Bernasconi & Maeder (1996). Uncertainties in both theory and observation, however, certainly dominate.

Moitinho et al. (2001) first employed the use of pre-main sequence isochrones to estimate the age of NGC 2362 by fitting the narrow sequence of low-mass stars with the models of Baraffe et al. (1998). Comparing the post-main sequence evolutionary models of Girardi et al. (2000) with the pre-main sequence isochrones of Baraffe et al. (1998), Moitinho et al. (2001) found agreement with an age of $5^{+1}_{-2}$ Myr. Dahm (2005) fit the narrow pre-main sequence of Hα emitters with the models of Baraffe et
| Authors                  | Age (Myr) | $M_V$ Range       | Isochrone<sup>a</sup> | $E(B-V)$ | Distance (pc) | Notes                           |
|-------------------------|-----------|-------------------|------------------------|----------|---------------|---------------------------------|
| Johnson (1950)          | ...       | $-7.0 \leq M_V \leq +4.0$ | ...                    | ...      | 1410          | UBV photometric                  |
| Johnson & Morgan (1953) | ...       | $-7.0 \leq M_V \leq +4.0$ | ...                    | 0.10     | 2090          | UBV photometry / spectroscopy   |
| Fenkart (1962)          | ...       | ...               | ...                    | 0.08     | 1620          | ugr                             |
| Perry (1973)            | ...       | $-7.0 \leq M_V \leq +1.0$ | ...                    | 0.10     | 1600          | uvby/β photometric               |
| Mermilliod (1981)       | ...       | $-7.0 \leq M_V \leq +1.5$ | ...                    | 0.11     | 1380          | Galactic cluster study          |
| Mermilliod & Maeder (1986)| 7.0     | $-7.0 \leq M_V \leq +1.5$ | Maeder (1981)          | 0.11     | 1622          | UBV photometric                  |
| Balona & Laney (1996)   | 5.0       | $-7.0 \leq M_V \leq +4.5$ | Meynet et al. (1993)   | 0.10     | 1490          | uvby/β CCD                       |
| Moitinho et al. (2001)  | 5.0       | $-2.0 \leq M_V \leq +10.0$ | B98 & G00              | 0.10     | 1480          | UBVRI CCD                        |
| Dahm (2005)             | 3.5-5.0   | $-2.0 \leq M_V \leq +10.0$ | DM97 & B98             | 0.10     | 1480          | VRI CCD and spectroscopic       |

<sup>a</sup> B98 - Baraffe et al. (1998), DM97 - D'Antona & Mazzitelli (1997), G00 - Girardi et al. (2000)
al. (1998) and D’Antona & Mazzitelli (1997). Differences in median ages between the models were noted by Dahm (2005), but an age of 3.5–5 Myr is in best agreement with the post main sequence age of \( \tau \) CMa and the main sequence contraction times for mid-to-late B-type stars. Perhaps most remarkable of the fundamental parameters of NGC 2362, however, is not its youth, but rather the small age dispersion evident within the cluster. Both Moitinho et al. (2001) and Dahm (2005) estimate an age dispersion of less than 3 Myr among the low-mass population, suggesting that star formation occurred rapidly, within a single burst. The coeval nature of the pre-main sequence population extends from the substellar limit to solar mass and intermediate mass stars. Much of the apparent dispersion in the CMD can be accounted for by multiplicity or observational errors, suggesting an even lower age spread. Similar narrow sequences are observed in other Galactic clusters, but NGC 2362 is among the least evolved to exhibit such a well-defined, coeval population.

4. The OB-Stellar Population of NGC 2362

As noted previously, the most massive member of NGC 2362 is \( \tau \) CMa (HD 57061, 30 CMa). Trumpler (1935) noted a radial velocity difference of \(+9.9 \text{ km s}^{-1}\) between it and other cluster members and interpreted this difference as a gravitational redshift induced by the star’s mass, calculated to be over 300 M\(_\odot\). More recent measurements have reduced the difference between the star’s \( \gamma \) velocity and the cluster radial velocity to \( \sim 8.0 \text{ km s}^{-1} \) (Van Leeuwen & van Genderen 1997). Some uncertainty can be accounted for by the multiple nature of \( \tau \) CMa. Struve & Pogo (1928) and Struve & Kraft (1954) found \( \tau \) CMa to be a single-line, spectroscopic binary (SB1), while Finsen (1952) discovered \( \tau \) CMa to be a visual pair composed of two stars separated by 0’’158. The Hipparcos catalog gives a separation of 0’’152 for the two stars and Hipparcos passband magnitudes of 4.887 and 5.329. Van Leeuwen & van Genderen (1997) propose that \( \tau \) CMa is a quadruple system, a composite of two binaries: the visual pair of O stars, the SB1 secondary of the brighter of the visual pair with a 154.9 day period and an eclipsing component with a period of 1.28 days. They further suggest that the composite system was formed through a merger of existing binaries. The multiple nature of \( \tau \) CMa and its evolved state certainly complicates interpretation of its position on the CMD.

The B-type main sequence population of NGC 2362 is believed to number around 40 stars, but membership cannot be confirmed without spectral type information or radial velocities for many of the candidate members. Surprisingly little modern work has been done on the B-star population of the cluster, with many of the available spectral types dating back to Johnson & Morgan (1953). Perry (1972) lists 14 early-type stars in the region as non-members on the basis of \( UBV \) photometry, but only nine of these lie within 5’ (~2 pc) of the cluster core. Of these nine, at least two are visual pairs and two others lie within 1’ of \( \tau \) CMa, raising the possibility of photometric errors induced by scattered light. Balona & Laney (1996) presented \( uvby/\beta \) CCD photometry of the cluster upper main sequence in their attempt to identify short-period \( \beta \) Cep-type variables. Although none were found, the photometry revealed a narrow ZAMS consisting of at least 25 stars extending from \( V \sim 7–12 \). The most recent investigation of the early stellar population of NGC 2362 is that of McSwain & Gies (2005) who examined 41 OB-type stars within the cluster vicinity for possible H\( \alpha \) emission using
Strömgren photometry. Only one candidate member, CD−24°5166, was identified as a possible emission source. Given the young age of NGC 2362, the dearth of classical Be stars within the cluster is consistent with the Be frequency-age dependence. NGC 2362 may lie within a narrow age region when the Herbig AeBe phenomenon has subsided and the classical Be line emission has not yet appeared. Table 2 lists approximately 40 early-type stars in the vicinity of τ CMa with their J2000 coordinates, spectral types, and B− and V−band photometry from SIMBAD. Spectral types for some stars taken from McSwain & Gies (2005) are listed simply as “B,” and should be regarded as uncertain.

5. The Initial Mass Function

Interest in NGC 2362 was renewed by Baade who remarked to Johnson (1950) that the cluster is composed almost exclusively of early-type stars and devoid of nebulosity. This point was emphasized by Baade in a lecture series given at Harvard Observatory in 1958 in which he used NGC 2362 as an example of a cluster with a mass function that clearly deviates from that of the field (Baade 1963). Consequently, Johnson (1950) conducted the first modern investigation of the cluster, determining a distance modulus from photoelectric magnitudes of the brightest cluster members of $m_V - M_V = 10.75$ (1410 pc). In their study of Galactic cluster luminosity functions, Vandenbergh & Sher (1960) supported Baade’s statement regarding the dearth of intrinsically low-luminosity stars in NGC 2362, but conceded that the photographic plates of the cluster obtained at Palomar Observatory were affected by the lights of San Diego. Another limitation discussed by Vandenbergh & Sher (1960) was their inability to consistently reproduce star counts, a systematic error that certainly scaled with stellar magnitude. In retrospect, the low response and poor quality of the photographic plates, the overwhelming brightness of the early-type cluster members, and the human factor introduced by the star counting process probably all contributed to the non-detection of the cluster’s faint stellar population. Consequently, Baade’s early commentary and the conclusions of Vandenbergh & Sher (1960) remained undisputed for another three decades.

The advent of CCD detectors brought about a revolution in observational astronomy, and with it a renewed search for an intrinsically faint stellar population around τ CMa. In March 1990 Wilner & Lada (1991) imaged NGC 2362 with the 90 in. telescope of Steward Observatory using an 800×800 pixel CCD camera. The challenges involved in direct imaging of the cluster, however, are considerable and deserve brief mention. Centrally located, the 4th mag τ CMa causes severe scattered light and charge blooming problems even on the shortest of integrations. These difficulties can be overcome with various imaging strategies (quadrants around τ CMa, combining multiple short exposures, etc.), but the faint stars in close proximity of τ CMa remain extremely difficult to observe. Wilner & Lada (1991) examined NGC 2362 using deep I−band imaging complete to $m_I \sim 16.6$. The interior 1.6′ of the cluster were excluded from the study because of severe internal reflections, but for the first time, a substantial population of faint stars (415) was detected around τ CMa. Despite the presence of these stars, however, Wilner & Lada (1991) concluded that a deficit of low-mass (<0.8 M⊙) stars relative to the Salpeter (1955) IMF was apparent. One possible explanation put forth by Wilner & Lada (1991) was that if the duration of star formation within NGC 2362 was longer than the age inferred from the evolutionary state of the B-type stars, mass segregation may have occurred, effectively moving low-mass members to...
Table 2
Candidate Early-type Members of NGC 2362

| Nr. | RA (J2000)    | δ (J2000)    | SpT  | B   | V   | Other Identifiers |
|-----|---------------|--------------|------|-----|-----|------------------|
| 68  | 07 18 21.94   | −24 51 11.9  | B3 IV/V | 8.80 | 8.94 | HD 56995         |
| 78  | 07 19 26.20   | −24 56 31.8  | B     | 10.73 | 10.71 | CD−24 5192       |
| 69  | 07 18 26.66   | −24 52 06.4  | Be?   | 9.99  | 10.06 | CD−24 5166       |
| 1   | 07 18 33.06   | −25 00 57.1  | B     | 11.39 | 11.40 | CPD−24 2195      |
| 2   | 07 18 34.26   | −24 56 45.6  | B     | 11.16 | 11.17 | CPD−24 2198      |
| 5   | 07 18 34.45   | −24 55 15.7  | B5 V  | 10.72 | 10.76 | CPD−24 2196      |
| 66  | 07 18 34.48   | −24 59 17.1  | B     | 11.44 | 11.46 | CPD−24 2199      |
| 11  | 07 18 35.62   | −24 55 22.3  | B     | 11.95 | 11.93 | CPD−24 2200      |
| 13  | 07 18 35.82   | −25 01 52.6  | B     | 10.59 | 10.59 | CPD−24 2201      |
| 9   | 07 18 35.95   | −24 59 35.0  | B3 V  | 9.76  | 9.80  | CD−24 5170       |
| 12  | 07 18 36.89   | −24 56 05.8  | B5 V  | 9.99  | 10.05 | CD−24 5172       |
| 48  | 07 18 37.48   | −24 57 42.2  | B3 V  | 9.43  | 9.54  | CPD−24 2205      |
| 15  | 07 18 38.13   | −24 59 01.5  | B9 V  | 11.79 | 11.75 | CD−24 5171       |
| 14  | 07 18 38.41   | −24 58 20.0  | B2 V  | 9.43  | 9.6   | CPD−24 2207      |
| 16  | 07 18 38.81   | −24 56 15.6  | B9 V  | 10.64 | 10.57 | QY CMa            |
| 70  | 07 18 40.19   | −24 58 49.3  | B     | 11.92 | 11.90 | CPD−24 2211      |
| 21  | 07 18 40.83   | −24 58 27.4  | B6 V  | 10.37 | 10.43 | CPD−24 2212      |
| 20  | 07 18 41.07   | −25 00 11.4  | B2 V  | 8.58  | 8.77  | CD−24 5175       |
| 95  | 07 18 41.55   | −24 57 44.8  | B     | 11.53 |       |                 |
| 39  | 07 18 41.99   | −24 58 12.3  | B2 V  | 9.69  | 9.78  |                 |
| 22  | 07 18 42.26   | −24 58 38.0  | B     | 11.95 | 11.91 |                 |
| 23  | 07 18 42.49   | −24 57 15.8  | O9 Ib | 4.25  | 4.39  | τ CMa            |
| 24  | 07 18 42.86   | −24 55 49.1  | B7 V  | 10.97 | 10.98 | CPD−24 2217      |
| 50  | 07 18 43.12   | −24 58 18.9  | B6 V  | 10.20 | 10.20 | CPD−24 2220      |
| 25  | 07 18 43.14   | −24 53 54.9  | B5 V  | 10.78 | 10.77 | CPD−24 2218      |
| 26  | 07 18 45.77   | −24 59 35.7  | B7    | 10.36 | 10.38 | CPD−24 2223      |
| 52  | 07 18 45.78   | −24 58 45.5  | B     | 11.97 | 11.91 | CPD−24 2222      |
| 27  | 07 18 46.20   | −24 57 47.6  | B3 V  | 10.10 | 10.15 | CPD−24 2225      |
| 30  | 07 18 48.54   | −24 56 56.0  | B1 V  | 8.04  | 8.21  | CD−24 5180       |
| 28  | 07 18 49.70   | −24 58 36.8  | B     | 12.07 | 12.05 | CPD−24 2229      |
| 31  | 07 18 49.83   | −24 57 48.7  | B2 V  | 9.20  | 9.31  | IM CMa           |
| 29  | 07 18 49.84   | −24 59 21.3  | B     | 11.31 | 11.33 | CPD−24 2230      |
| 56  | 07 18 52.79   | −24 55 12.2  | B     | 12.14 | 12.01 | CPD−24 2234      |
| 34  | 07 18 53.22   | −24 57 23.2  | B5 V  | 10.47 | 10.50 |                 |
| 58  | 07 18 54.57   | −24 57 29.1  | A0    | 12.30 | 12.23 |                 |
| 57  | 07 18 54.71   | −24 56 18.1  | B     | 12.18 | 12.16 | CPD−24 2237      |
| 36  | 07 18 58.44   | −24 57 41.1  | B3 V  | 10.78 | 10.76 | CPD−24 2240      |
| 42  | 07 19 04.93   | −24 56 15.1  | B     | 11.32 | 11.34 | CPD−24 2244      |
| Anon| 07 19 12.62   | −24 51 57.0  | B     | 12.17 |       |                 |
| 46  | 07 19 12.77   | −24 57 20.5  | B2 V  | 6.630 | 6.801 | HD 57192         |
| 76  | 07 19 16.75   | −24 53 31.4  | B     | 9.76  | 9.80  | CPD−24 2250      |
| Anon| 07 19 19.39   | −24 52 29.4  | B     | 11.95 |       |                 |

*a Number from Johnson (1950)*
the outer cluster regions where the survey was incomplete. Kroupa, Gilmore, & Tout (1992) re-examined the luminosity function (LF) of NGC 2362 presented by Wilner & Lada (1991), comparing it to the solar neighborhood mass function regressed to an age of 10 Myr. Their modeled LF was found to be in agreement (within error) with that observed for NGC 2362, suggesting that the cluster mass function is similar to that of the field star population. The full extent of the low-mass population was not realized until Moitinho et al. (2001) presented their CMD of the cluster. Recently, however, the possibility of a non-standard IMF for NGC 2362 was again raised by the deep Chandra survey of the cluster by Damiani et al. (2006b). Their analysis of cluster X-ray sources finds a real deficit of low-mass stars compared to a power law or a log-normal distribution. When compared to IC 348 or the Orion Nebula Cluster, the IMF of NGC 2362 appears to be significantly different.

Figure 4. A $V, V−I$ color-magnitude diagram of NGC 2362, from Moitinho et al. (2001). The line on the left is the 5 Myr post-main sequence isochrone from Girardi et al. (2000) and the lines on the right are the 5 Myr pre-main sequence isochrone of Baraffe et al. (1998) and the upper limit of the binary sequence, 0.75 mag. more luminous. The large solid point in the top-left corner of the figure represents τ CMa.
6. The Low-Mass Population of NGC 2362

The $UBVRI$ photometric survey of NGC 2362 of Moitinho et al. (2001) revealed the long, narrow pre-main sequence of stars extending more than 9 mag in the CMD from $V \sim 11$ to 20, corresponding to early-A spectral types to nearly the hydrogen burning limit. Shown in Figure 4 is the $V, V - I$ CMD of NGC 2362 taken from Moitinho et al. (2001). The solid line to the left is the 5 Myr post-main sequence isochrone of Girardi et al. (2000), and the two parallel lines to the right are the 5 Myr isochrone of Baraffe et al. (1998) and its complementary binary sequence limit lying 0.75 mag. above. The Baraffe et al. (1998) 5 Myr isochrone fits the cluster pre-main sequence well, but is truncated near $V - I \sim 2.2$ to avoid complications with the models. The deep $VRI$ photometric survey by Dahm (2005) extended the cluster pre-main sequence another two magnitudes, finding nearly 500 stars (undoubtedly including many field interlopers) lying above the ZAMS. Shown in the left panel of Figure 5 is the $V, V - I$ CMD for all stars in the Dahm (2005) photometric survey. The narrow pre-main sequence discovered by Moitinho et al. (2001) is strongly evident and densely populated, to the substellar limit. The solid line in the panel is the Pleiades main sequence and the upper main sequence of Balona & Shobbrook (1984).

![Figure 5](image-url)

Figure 5. The $V - I_c, V$ color-magnitude diagrams of NGC 2362 for all stars observed by Dahm (left) and for just the H$\alpha$ emitters (right). No allowance has been made for interstellar extinction. The solid line in each panel is the Pleiades main sequence from Stauffer (1984) and placed at the adopted cluster distance of 1480 pc.
Given the relative youth of the cluster, the low-mass stellar population of NGC 2362 should still be in its T Tauri phase of evolution, either actively accreting circumstellar gas or experiencing enhanced chromospheric activity. G. H. Herbig (private communication) first undertook a slitless grism survey of the cluster in 1991, and despite the low dispersion of the survey, 6.6 Å pixel$^{-1}$, two H$\alpha$ emitters were detected in the cluster. Follow-up slitless grism and Gemini multi-object spectrograph (GMOS) surveys by Dahm (2005) detected an additional $\sim$130 H$\alpha$ emitters. These moderate-resolution GMOS spectra were also adequate for the determination of Li I $\lambda$6708 line strengths, thereby permitting confirmation of youth for many of the H$\alpha$ emission population. Most of the H$\alpha$ emitters identified within the cluster lie along the narrow pre-main sequence of stars in the CMD, as shown in the right panel of Figure 5. Comparing the left and right panels of Figure 5, we see that perhaps 200–300 more low-mass candidates lie near the established cluster sequence. Deeper optical surveys are currently underway by several groups, which will almost certainly identify most low-mass and very low-mass cluster members. The Monitor project of Irwin et al. (2008) is a deep, time-series photometric survey of NGC 2362 used to derive rotation periods for 271 cluster members with masses between 0.1 and 1.2 M$_\odot$. The same data set was incorporated into the search for transiting planets by Miller et al. (2008) which identified six stars with potential planetary transit events.

7. The Cluster Mass

Given the apparent absence of molecular gas and H II emission in the cluster vicinity, the mass of NGC 2362 should be dominated by its stellar population. The first attempt at establishing a cluster mass was made by Lohmann (1977) who performed a star count and LF analysis of the cluster and derived a total cluster mass of 246 M$_\odot$ by summing down to $M_V$ $\sim$5.8. Bruch & Sanders (1983) subsequently used Lohmann’s mass for NGC 2362 as a calibrator in their determination of absolute masses of open clusters and OB associations. Muench (2002) constructed the $K$-band luminosity functions of NGC 2362, IC 348, and the Orion Nebula Cluster, finding the underlying mass functions of each to be remarkably similar. While the total stellar mass of NGC 2362 is certainly less than that of the ONC (930-1860 M$_\odot$: Hillenbrand 1997), it is probably somewhat greater than that of IC 348 ($\sim$200 M$_\odot$: Lada & Lada 1995). Mass estimates for the quadruple system that comprises $\tau$ CMa alone range from 30 to 90 M$_\odot$ (van Leeuwen & van Genderen 1997). Assuming that only early-type stars on or near the ZAMS of the cluster are bona fide members, a total of $\sim$200 M$_\odot$ can be accounted for within the cluster’s B-star population. When added to the mass of $\tau$ CMa, this value agrees well with the cluster mass derived by Lohmann (1977).

To estimate the total mass of the cluster pre-main sequence population, the masses for the individual H$\alpha$ emitters were summed by Dahm (2005) to yield a model-dependent value of 45–72 M$_\odot$. This is certainly a lower-limit given the larger population suggested by the CMD. An upper limit for the total mass of the pre-main sequence population is given by the sum of masses for all stars lying between the 1 and 10 Myr isochrones of Baraffe et al. (1998). This estimate very likely includes many field interlopers and excludes some stars that appear overluminous due to multiplicity. The total mass of the $\sim$500 stars falling within these isochrones is $\sim$300 M$_\odot$. Adding the derived upper and lower limits for the pre-main sequence population to the mass of the B-stars and the mass of $\tau$ CMa, the total cluster mass probably ranges from $\sim$300 to 540 M$_\odot$. These
estimates, however, do not account for the A and early F-type stars, which are still on their radiative tracks. Reviewing the CMDs shown in Figures 4 and 5, around two dozen stars have been excluded from the pre-main sequence analysis, which may be members of this intermediate-mass population. Assuming an average mass of 2 $M_\odot$ for each, this would amount to another $\sim 50 M_\odot$. Allowing for multiplicity, outlying members, and the very low-mass population below the completeness limit of the photometric surveys, the stellar mass of the cluster is likely substantially greater.

8. Infrared Observations of NGC 2362

Haisch, Lada, & Lada (2001) included NGC 2362 in their $JHKL$-band survey of young clusters and concluded that the disk fraction of low-mass members as inferred from infrared excesses is $12 \pm 4\%$. From the ages of their cluster sample, Haisch et al. (2001) claimed an upper limit for inner disk lifetimes of $\sim 6$ Myr, with half of all stars losing their disks within 3 Myr. Their findings were critically dependent upon the disk fraction of NGC 2362, where their $L$-band survey was complete only to $\sim 1 M_\odot$. These ground-based observations, however, are sensitive to only the innermost disk regions ($\ll 1$ AU). The infrared excess-derived inner disk frequency does agree well with the fraction of TTSs within the cluster that are classical TTSs, $\sim 9\%$. While some of these strong H$\alpha$ emitters can be accounted for by enhanced chromospheric activity, a handful are definitive accretors as evidenced by their complex optical spectra. Spitzer InfraRed Array Camera (IRAC) observations of NGC 2362 were used by Dahm

![Figure 6](image)

Figure 6. From Dahm & Hillenbrand (2007), the IRAC-derived 8.0 to 4.5 $\mu$m flux ratio plotted as a function of $J-H$ color for all suspected members of NGC 2362 with 8.0 and 4.5 $\mu$m photometric errors of $< 0.2$ mag. The larger scatter about the abscissa for the lower mass stars arises from sensitivity limits at 8 $\mu$m, which tend to deflect the distribution toward more negative flux ratios. None of the higher mass stars with $J-H < 0.5$ (K2 spectral type) exhibit significant infrared excess for $\lambda < 8.0 \mu$m.
& Hillenbrand (2007) to examine 232 suspected cluster members drawn from known Hα emission stars. X-ray-detected stars from the 100 ks archival Chandra observation, and established lithium-rich stars to identify the remnant disk-bearing population of the cluster. Dahm & Hillenbrand (2007) derive an upper limit for the primordial, optically thick disk fraction of NGC 2362 of ∼ 7 ± 2%, with another ∼ 12 ± 3% of suspected members exhibiting infrared excesses indicative of weak or optically thin disk emission. The presence of circumstellar disks among candidate members of NGC 2362 was also found to be strongly mass-dependent, such that no stars more massive than ∼1.2M⊙ exhibit significant infrared excess shortward of 8 μm. This is clearly demonstrated in Figure 6, which plots the logarithm of the ratio of the 8.0 and 4.5 μm fluxes as a function of J − H color, a tracer of stellar photospheric emission. From Hα emission line strengths, Dahm & Hillenbrand (2007) placed an upper limit for the accretion fraction of the cluster at ∼5%, with most suspected accretors being associated with primordial, optically thick disks. The low-mass population of NGC 2362 is passing through a critical era in the empirically established disk evolutionary scenario when most stars have already dissipated their inner circumstellar disks. NGC 2362 has yet a vital role to play in our understanding of disk dissipation timescales and the formation of planetary systems.

9. X-ray Observations of NGC 2362

X-ray observations of NGC 2362 were first made by Berghofer & Schmitt (1998) using ROSAT to examine the low-mass population of the cluster. In an 83 ks PSPC integration, 229 sources were detected within a radius of 36′ of τ CMa. The inner 2′ remained unresolved, but a later 87 ks exposure with HRI was able to isolate sources within close proximity of τ CMa. The most luminous X-ray sources of the ROSAT survey were the two O-stars, τ CMa and 29 CMa lying ∼30′ to the north. Correlating the X-ray detections with the Digitized Sky Survey, Berghofer & Schmitt (1998) concluded that the majority of emitters were associated with optically faint (V > 12 mag.) stars. The X-ray luminosity function for the low-mass stars in NGC 2362 was found to be consistent with that found in the Chamaeleon star forming region by Alcala et al. (1997). These early ROSAT surveys, however, were hampered by low sensitivity and spatial resolution, making source identification within the densely clustered environment of NGC 2362 difficult. The Chandra X-ray Observatory has revolutionized X-ray astrophysics with sensitivities an order of magnitude greater than older missions, sub-arcsecond-scale spatial resolutions, and energy-band coverage from 0.1–10.0 keV. A deep (97.9 ks) Chandra ACIS-I observation of NGC 2362 was completed on 2004 December 23–24 by Damiani et al. (2006a,b) who identified 387 X-ray sources down to logL_X = 29.0 within the ACIS-I field of view. Damiani et al. (2006b) find a significantly wider spatial distribution of low-mass stars relative to more massive stars within the cluster, suggesting that mass segregation is occurring. As discussed in Sect. 5, they also conclude that the cluster mass function flattens significantly with respect to other young clusters.

Delgado et al. (2006) using the same Chandra ACIS-I observation in conjunction with deep UBVRI_C and 2MASS JHK_S photometry assign a membership status to nearly 200 X-ray detected sources within the cluster. Their findings suggest clearly distinct X-ray activity behaviors between pre-main sequence and main sequence cluster members. Among pre-main sequence stars, L_X and L_Bol are strongly correlated as
would be expected, but main sequence cluster members show no correlation between these two properties. Damiani et al. (2006b) also find X-ray spectral differences between stars brighter or fainter than $\log L_X \sim 30.3$ such that more X-ray luminous stars exhibit a hotter ($kT \sim 2$ keV) temperature component, not present in the fainter population. With no additional Chandra or XMM-Newton observations of NGC 2362 planned in the near future, it is likely that no further enlargement of the X-ray membership sample will occur below the current X-ray completeness limit of $\sim 0.4 M_\odot$.

10. Concluding Remarks

Over the last half-century, NGC 2362 has played an extraordinary role in our understanding of the star formation process. Early perceptions of an anomalous mass function were overturned with the advent of modern detectors. Deep CCD surveys of the cluster by Wilner & Lada (1991) and Moitinho et al. (2001) revealed a well-populated, pre-main sequence extending more than 9 mag to nearly the substellar limit. There are new indications, however, that a deficit of low-mass stars is present within the cluster, implying that the IMF issue has yet to be fully resolved. Recent Chandra X-ray observations of NGC 2362 have added several hundred more pre-main sequence candidates to the $\sim 100+$ suspected members exhibiting H$\alpha$ emission or strong Li I $\lambda 6708$ absorption. Deeper optical and infrared surveys of the cluster will also push the source detection threshold into the brown dwarf regime, permitting a closer examination of the cluster IMF. Interest in NGC 2362 has also shifted to the remaining optically thick circumstellar disks around low-mass cluster members. Near infrared and H$\alpha$ emission surveys suggest that the inner disk regions have dissipated for most ($\sim 90\%$) of the suspected cluster members as evidenced by the decay of near infrared excess and strong H$\alpha$ emission. Spitzer observations are beginning to resolve the remaining questions of disk frequency within the cluster. It is perhaps somewhat ironic that in the process of identifying and characterizing the low-mass population of NGC 2362 over the last decade, the OB stars have been somewhat neglected. McSwain & Gies’ (2005) recent Strömgren photometric survey of 41 OB-type stars in the cluster region found only one candidate classical Be star. A more thorough spectroscopic analysis of the B-star population is needed to confirm spectral types, evaluate membership, and to examine questions of binarity, critical to understanding the placement of stars on the ZAMS. NGC 2362 will likely remain a favored target for ground-based and space-based observations. Its large, statistically-significant population of low-mass, pre-main sequence stars, its well-defined upper main sequence, compact structure, and lack of circumstellar and interstellar gas and dust relative to similarly aged clusters all contribute to the cluster’s unique nature.

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