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Young Stars in NGC 6231 and the Sco OB1 Association

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Abstract. NGC 6231 is a young cluster in the southern sky, around 3-5 Myr old, located at a distance of about 1.6 kpc at the near side of the Sagittarius spiral arm. It forms the nucleus of the extended Sco OB1 association. The cluster is very rich, with more than 100 massive stars, among them 15 O-stars. Radial velocity studies have revealed a very large binary fraction among these OB stars. The young low-mass population has recently been identified using deep X-ray observations. Within the large HII region Gum 55 that surrounds NGC 6231 there exists a major elephant trunk, which shows evidence for recent second-generation star formation in the form of young B-stars surrounded by reflection nebulae and a number of low-mass Hα emission stars.

1. Introduction

The open cluster NGC 6231 (also known as De Cheseaux No. 9, Lacaille II.13, Dunlop 499, Melotte 153, and Collinder 315) in Scorpius was first discovered by Giovanni Battista Hodierna, who included it in his 1654 "*De systemate orbis cometici; deque admirandis coeli characteribus*" [Of the systematics of the world of comets, and on the admirable objects of the sky]. Subsequently, NGC 6231 was independently discovered by Edmond Halley, who included it as one of three nebulous objects in his 1678 catalog of southern stars (Ashworth 1981). In about 1746, Philippe Loys de Chéseaux prepared a list of 21 nebulae, including his independent discovery of NGC 6231. Finally, NGC 6231 was again independently discovered by Abbe Nicholas Louis de la Caille and published in his 1755 catalog "*Sur les étoiles nébuleuses du Ciel Austral*" [On the Nebulous Stars of the Southern Sky]. Subsequently, this open cluster was cataloged by several other researchers, including in John Herschel's "*Results of Astronomical Observations made at the Cape of Good Hope*" of 1847 (where it was listed as h3652), until it was included in the New General Catalogue by J.L.E. Dreyer in 1888 and given the identifier NGC 6231 under which it is known today. For further historical details, see http://www.seds.org/messier/xtra/ngc/n6231.html.

The Sco OB1 association, earlier known as the I Sco association (Morgan, Whitford, & Code 1953), is an extensive grouping of OB stars centered on l = 343.3° and b = 1.2° at the near side of the Sagittarius spiral arm. NGC 6231 is the nucleus of this OB association, and excites the extended HII region Gum 55.

2. Distance and Age

Due to the richness of NGC 6231, a substantial number of distance estimates have been made. The earliest distance determinations, of historical interest only, are listed in the *Catalogue of Star Clusters and Associations* by Alter et al. (1970).

Figure 1. The NGC 6231 cluster is located just beneath the center of the image and is surrounded by the ring-shaped HII region Gum 55. The bright HII region to the upper left is IC 4628. The Large Elephant Trunk is seen towards the upper right pointing towards the central cluster. The field is approximately 3.5 by 3.5 degrees. North is up and east is left. Courtesy Johannes Schedler.

One of the first accurate distance measurements was performed by Bok, Bok, & Graham (1966), who obtained UBV and Hβ photometry of 43 stars, leading to a suggested distance for the Sco OB1 association of about 1800 pc. Feinstein & Ferrer (1968) did UBV photometry of 15 stars in the NGC 6231 cluster itself for which MK spectral types were available, and determined a distance of 1900$\pm$150 pc. Crawford et al. (1971) obtained uvbyβ photometry for 110 probable member stars, and found a distance of 2.0 kpc. Schild, Neugebauer, & Westphal (1971) used both existing and new data to suggest a distance modulus of 11.9$\pm$0.3, corresponding to 2.4 kpc. Garrison & Schild (1979) obtained UBV photometry and MK classifications of 30 stars to estimate a distance of about 2100 pc. Shobbrook (1983) obtained uvbyβ photometry of

50 members, covering from early B supergiants to B9 dwarfs, and found a distance of 1.6 kpc. In a simultaneous study, van Genderen et al. (1984) used VBLUW photometry of about 130 members to estimate a distance to the Sco OB1 association of 1600±200 pc, finding no difference between the distance to NGC 6231 and the overall Sco OB1 association. Perry et al. (1991) analyzed all existing data up to that time, and suggested a distance of 2.0 kpc. Balona & Laney (1995) used new uvbyβ photometry to determine a distance modulus of 11.08±0.05, or about 1650 pc. Raboud et al. (1997) used Geneva photometry over an extended field around NGC 6231 to identify additional cluster members, and determined a cluster distance of 1800 pc. Sung et al. (1998) used UBVRI and Hα CCD photometry to identify pre-main sequence stars in NGC 6231, found a broad peak in the distance moduli at $V_o - M_V$ = 10.7-11.1, and adopted the distance modulus of NGC 6231 as 11.0±0.07, corresponding to 1.6 kpc. Following up on an early suggestion by Breckinridge & Kron (1963), Sung et al. demonstrated that the extinction is varying across the cluster, with more reddening towards the southern part of the cluster. Recently Baume et al. (1999) used UBVI CCD photometry of more than 1000 stars and adopted a distance of 1900±200 pc. Makarov (2003) used Hipparcos parallaxes of bright members of NGC 6231 to determine a distance modulus of 8.9±0.5, suggesting a very close distance of only about 600 pc, but Schröder et al. (2004) have pointed out difficulties in using parallaxes for O-stars. Finally, both Sana et al. (2005) and Bouzid, Sterken, & Pribulla (2005) analyzed the eclipsing binary CPD-41°7742 = V1034 Sco, and suggested a distance of 1530±110 pc and 1400 pc, respectively.

The variation in distance values reflect observational uncertainties, unresolved binaries, different estimates of the (patchy) extinction, and evolving calibrations. It is obviously difficult to evaluate which of the above studies provide the more accurate distance values, but it seems safe to say that the cluster is located between 1.4 and 2.0 kpc, with a value of 1.6 kpc being commonly used in the recent literature, a value that is adopted in the following.

The age of NGC 6231 has been estimated by various authors using a variety of methods (ZAMS turn-off, isochrone fitting, appearance of Wolf-Rayet features) and different mass-ranges, and the resulting ages are listed in the following: 3.6±0.6 Myr (van Genderen et al. 1984), 7.9±4 Myr (Perry et al. 1991), 4.5 Myr (Santos & Bica 1993), 3.8±0.6 Myr (Raboud et al. 1997), 2.5-4 Myr (Sung et al. 1998), 3-5 Myr (Baume et al. 1999). These age estimates are principally derived based on the massive stars in the cluster. Sung et al. (1998) argue that there are indications for very large age spreads among the lower mass stars, ranging from about 1 Myr to 12 Myr. Despite the uncertainties, there is a consensus that NGC 6231 comprises a very young massive cluster, and as such it deserves further detailed study.

3. The Young Massive Stars

The Sco OB1 association contains a large number of O and B stars, Morgan et al. (1953) identified seventy OB stars towards the NGC 6231 region. Braes (1967) use proper motions to isolate cluster members. Humphreys (1978) lists 28 OB giants and supergiants in the association, among them two of the most luminous OB stars known, HD 151804 (O8Iaf) and HD 152236 (B1.5Ia). Ankay et al. (2001) list the most probable members based on Hipparcos data. The rich cluster NGC 6231 forms the nucleus of the Sco OB1 association (see Figs. 1 and 2) and the cluster itself contains over 100

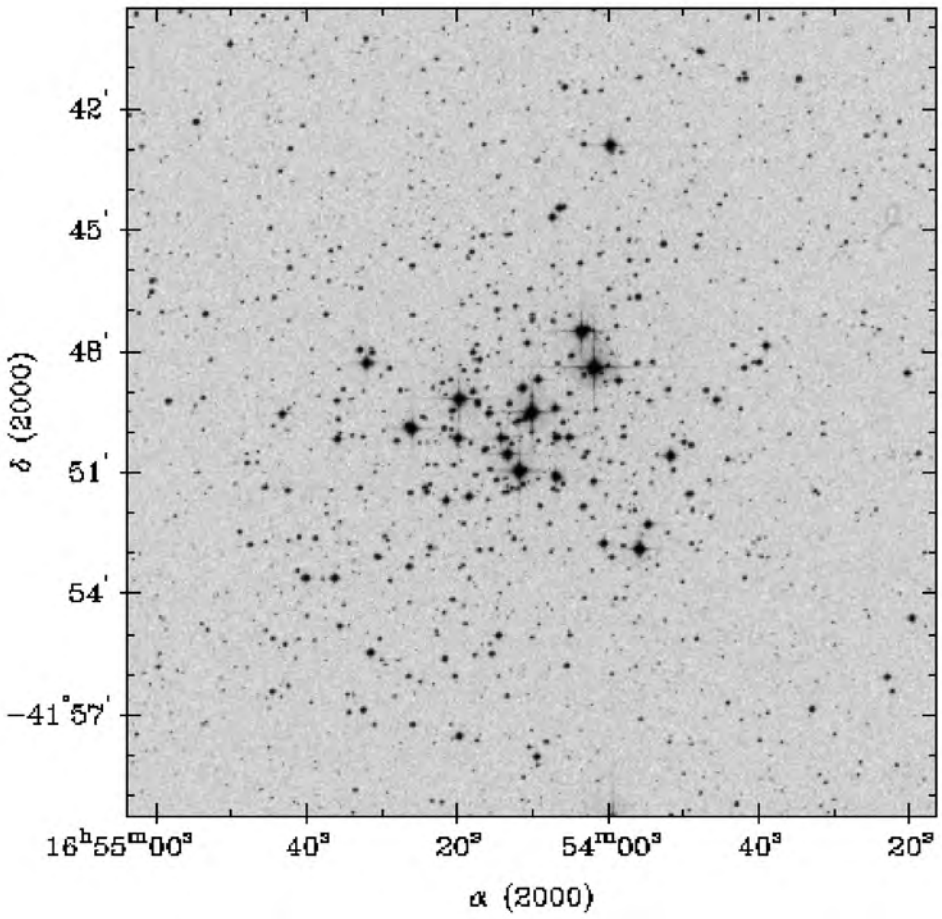

Figure 2. A red plate of the NGC 6231 cluster from the Digitized Sky Survey. The area shown is $20' \times 20'$.

massive stars, including 15 O stars (Shobbrook 1983). MK spectral types of all the brighter stars are given by Garrison & Schild (1979), Levato & Malaroda (1980), and Sana et al. (2006b).

HD 152248 (V1007 Sco) is a bright (V=6.1) O star at the center of the cluster, and the brightest X-ray source in the cluster. It was found to be a spectroscopic binary by Struve (1944), and eclipses were found by Mayer et al. (1992). Orbital elements were derived by, among others, Stickland et al. (1996), Penny et al. (1999), Sana et al. (2001), and Mayer et al. (2008). The individual components are classified as O7.5 III(f) + O7.5 III(f), each with masses of almost 30 $M_{\odot}$, and an orbital inclination of 67°. The period is only 5.8 days, and the small separation of the components lead to significant wind-wind interactions (e.g., Sana et al. 2004). Another massive star, CPD−41°7742 = V1034 Sco, which is an O9 V + B1 V pair, was found to be a second double-lined eclipsing binary in NGC 6231 (Sana et al. 2003, 2005, Bouzid, Sterken, & Pribulla 2005). This system also has wind-interactions, with the powerful wind from the O9 primary crashing onto the surface of the secondary (Sana et al. 2005). Recently, a third

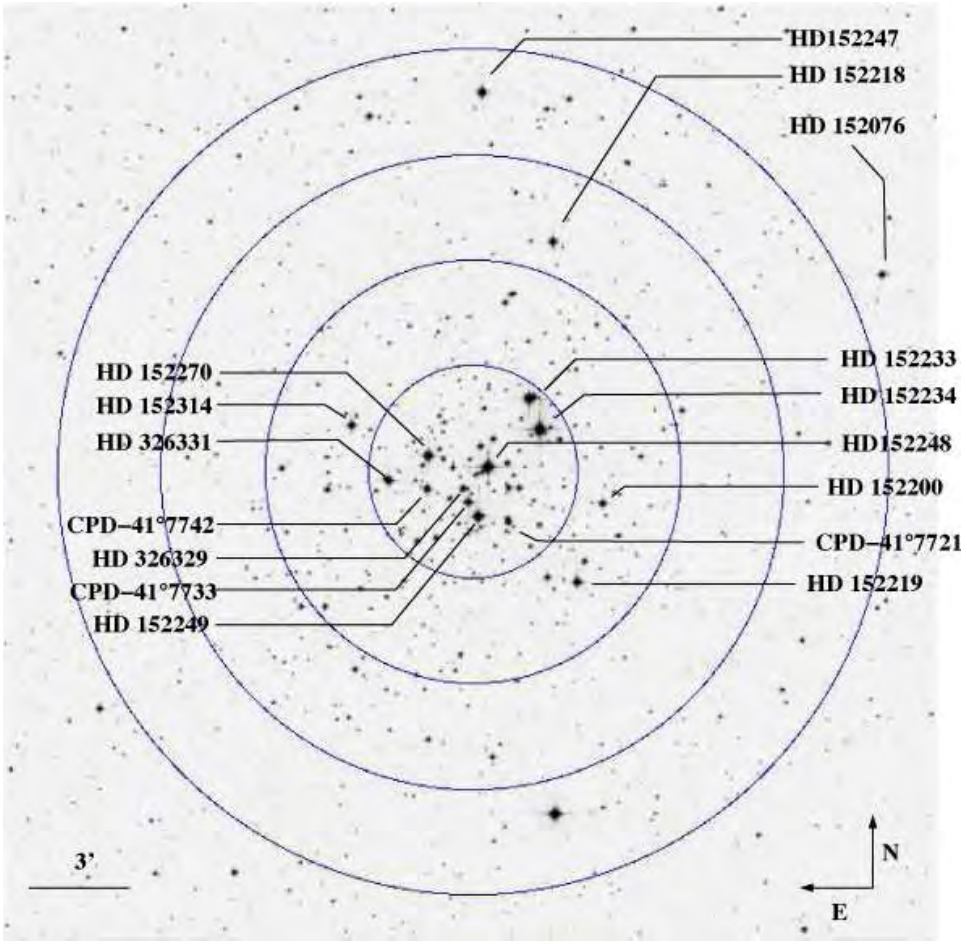

Figure 3. Identification of the 15 O-type stars and one Wolf-Rayet star (HD 152270) in the NGC 6231 cluster. The concentric circles are centered on the cluster core with radii of 1×, 2×, 3×, and 4× the cluster core radius of about 1.5 pc. From Sana et al. (2008b).

double-lined eclipsing OB binary, HD 152219, was found in the cluster (Sana, Gosset, & Rauw 2006c).

Considerable interest has been focused on the binarity of the massive stars in NGC 6231. Numerous spectroscopic binaries have been identified in the cluster (e.g., Struve 1944, Hill et al. 1974, Levato & Morrell 1983, Raboud 1996, Garcia & Mermilliod 2001, Sana et al. 2007b, 2008a), and Garcia & Mermilliod (2001) and Sana et al. (2008b) found that more than half of the O stars are binaries with short periods less than 10 days, a result that eventually may lead to insights into the formation of massive stars. Mayer et al. (2008) noted that there are ten known eclipsing binaries in NGC 6231.

A particularly interesting binary is HD 153919 = V884 Sco, an O6.5 Iaf$^+$ runaway star located towards the neighboring 125 million yr old cluster NGC 6281 (Feinstein & Forte 1974), but with an origin in the Sco OB1 association near the NGC 6231 cluster (Feinstein & Forte 1974, Ankay et al. 2001), see Figure 4. Jones et al. (1973) dis-

covered that HD 153919 has an X-ray companion 4U1700-37, which together form an eclipsing high-mass X-ray binary. The compact companion is either a massive neutron star or a low mass black hole (Clark et al. 2002).

NGC 6231 also contains a number of chemically peculiar stars (e.g., Keenan et al. 1984, Massa et al. 1984).

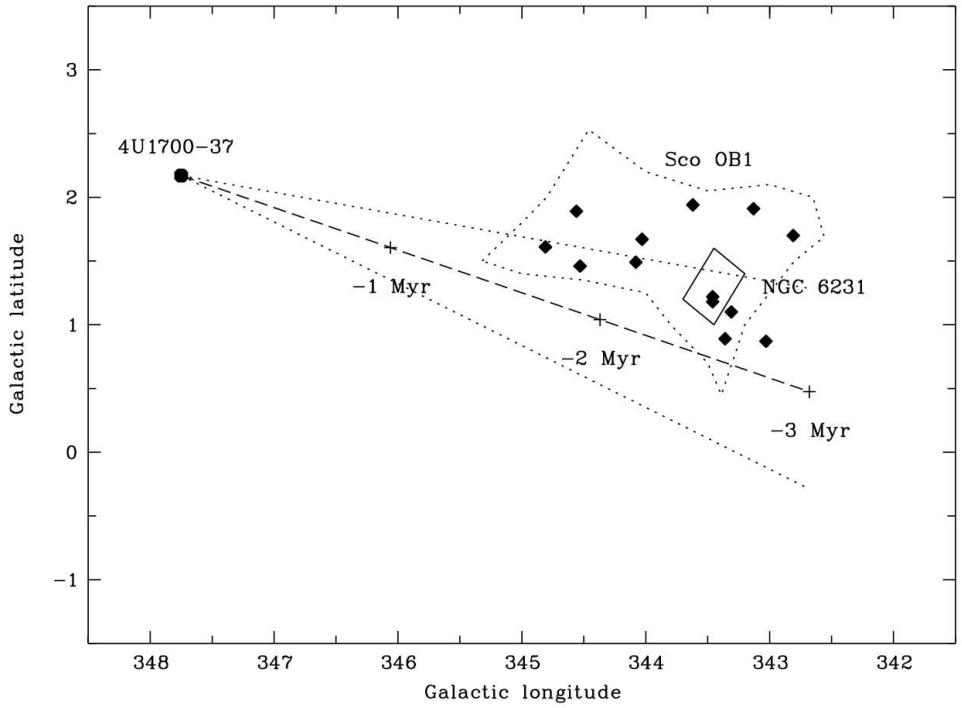

Figure 4. The location of the runaway star HD 153919 in relation to NGC 6231 and its reconstructed path. From Ankay et al. (2001).

4. The Young Low-Mass Population

At a distance of about 1.6 kpc, it is not so easy to detect and extract the low-mass pre-main sequence population of NGC 6231 from the rich back-ground star fields. With ages determined for the massive stars in the range 3-5 Myr, one would expect that there would still be a very substantial population of T Tauri stars at faint magnitudes. In an attempt to detect Hα emission stars photometrically through an R$-$Hα color, Sung et al. (1998) found only 12 stars with Hα emission, and another 7 Hα emission candidates. This is far less than expected, and led Sung et al. to speculate that the lower end of the IMF in NGC 6231 could be truncated.

In a more recent study, Sana et al. (2006a,b, 2007a) have given results of a major 180 ks XMM-Newton X-ray observation of the NGC 6231 cluster. Figure 5 shows the resulting EPIC-MOS image revealing, in addition to the bright X-ray sources from the early-type stars, hundreds of X-ray point-sources that surround the center of the cluster, thus indicating that they come from a population of young low-mass stars. Figure 6 shows a Hertzsprung-Russell diagram by Sana et al. (2006d, 2007a) using the optical

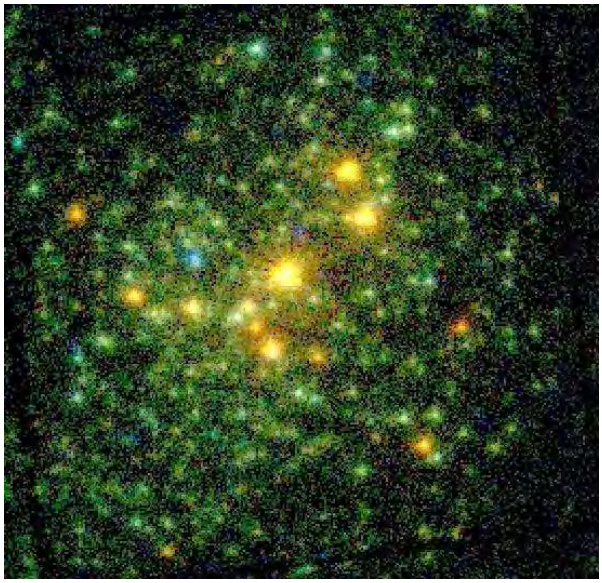

Figure 5. The NGC 6231 cluster from an EPIC-MOS X-ray image from XMM-Newton. The field shown is about $10' \times 10'$. From Sana et al. (2006a).

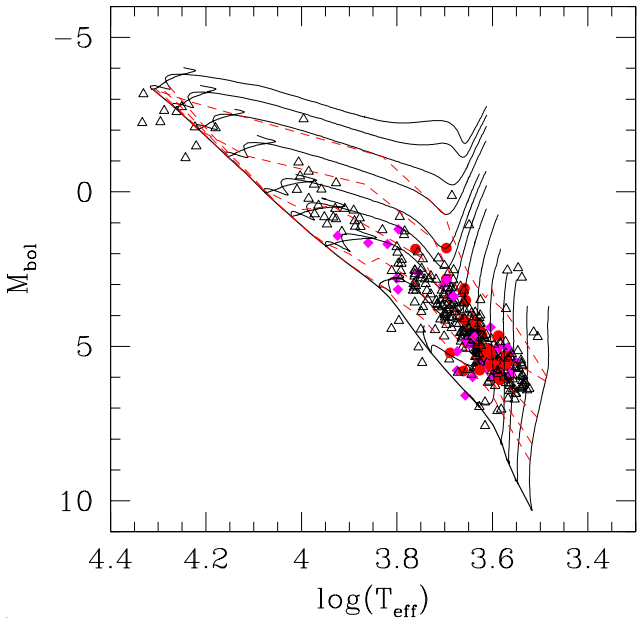

Figure 6. A Hertzsprung-Russell diagram of the EPIC sources in the NGC 6231 cluster with optical counterparts in the Sung et al. (1998) catalog. Filled red dots, filled magenta diamonds, and open triangles indicate Hα emission stars, Hα emission candidate stars, and other stars, respectively. The ZAMS is the thick solid line, and evolutionary tracks from Siess et al. (2000) are overlaid. From Sana et al. (2006d, 2007a), where full details are given.

counterparts to the X-ray sources observed by Sung et al. (1998). The location of the sources is consistent with a several million year old population of low-mass stars approaching the main sequence. The analysis by Sana et al. (2006a,b, 2007a) indicates that star formation in NGC 6231 started at least 10 Myr ago and increased until a starburst-like event a few million years ago, at which time the population of massive stars were formed. These results suggest that NGC 6231 may harbor a large low-mass PMS population, and that the IMF may not be truncated after all.

Attempts have been made to identify a population of lower-mass stars scattered throughout the Sco OB1 association. The bulk of the distributed OB stars in the association is found to the north of NGC 6231, and it has been suggested that they form a large sparsely populated open cluster sometimes known as Tr 24 (Seggewiss 1967). The physical reality of this loose grouping has been disputed by Perry et al. (1991). Heske & Wendker (1984, 1985) found a group of fainter stars that their observations indicated could be low- to intermediate-mass pre-main sequence stars. Piers et al. (1992), however, suggest the possibility that most of these stars are located in the foreground of NGC 6231.

It is evident that both NGC 6231 and the Sco OB1 association are ripe for detailed investigations to further identify and study the low-mass pre-main sequence population.

5. The Atomic and Molecular Gas

NGC 6231 is surrounded by a large HII region, known as Gum 55 (Gum 1955), as pointed out by Bok, Bester, & Wade (1955). In a follow-up study, Bok, Bok, & Graham (1966) note (see Fig. 1): "*The unusual HII region ... is roughly in the form of an elliptical ring, about 4° by 5° in extent, centred on the cluster NGC 6231. The emission nebula is faint within the ring but is very bright where the ring is crossed by the northern extremity of the association.*" The HII region is also known as RCW 113 (Rodgers, Campbell, & Whiteoak 1960).[1] Part of the HII region is included in the Fabry-Perot maps of the southern Milky Way by Georgelin et al. (1996). Sivan (1974) found faint outlying Hα emission features.

Bronfman et al. (1989) performed a CO survey of the Galactic plane from Galactic longitude l = 300° to 348° and Galactic latitude b = $-2°$ to 2°. This includes the region of NGC 6231 (l = 343.5°, b = 1.2°), at which location there are clouds observed at V_{lsr} = -25 km/sec and -65 km/sec. The latter is a line-of-sight cloud, but the former is likely to come from gas in the general Sco-Cen region, since the velocity is consistent with the velocities of the Hα emitting gas studied by Georgelin et al. (1996). Yamaguchi et al. (1999) surveyed a small region within the northern part of the HII region and found a molecular cloud (their region 20, cloud 81) associated with several IRAS sources.

In an extinction survey, Neckel & Klare (1980) found a sharp increase in the extinction ($A_V \sim 0.75$ mag) towards the Sco OB1 association at a distance between 100 and 300 pc, presumably linked to the gas in the Lupus region. A second sharp increase in extinction (again $A_V \sim 0.75$ mag) occurs at a distance of 700 to 1000 pc, after which

[1] Occasionally this large ring-shaped HII region is called IC 4678 (e.g., Schild et al. 1969, Perry et al. 1990, Feinstein et al. 2003). This is not correct, since the original IC catalogue (vol. II) shows that IC 4678 is located near M8.

Figure 7. The HII region IC 4628. North is up and east is left, and the field is approximately $55' \times 65'$. Image combined from Hα, [SII], and [OIII] filter images. Courtesy Martin Pugh.

there appears to be no more significant extinction out to the cluster. Marggraf et al. (2004) studied the gas towards 7 stars in the direction of NGC 6231 using ultraviolet spectra from FUSE. The main absorption they find is associated with the nearby Lupus extinction, but a second weaker one appears to be from a shell of gas surrounding NGC 6231. Differences between the lines-of-sight suggest that the gas is separated into smaller cloudlets. Crawford (2001) noted, in a similar study, that there is no evidence for active shocks in the observed shell components. In a recent study, Galazutdinov et al. (2008) found that various diffuse interstellar bands towards Sco OB1 are blueshifted by 6 - 10 km s^{-1}. Earlier analyses of gas in the line-of-sight to NGC 6231 include the studies of Crawford et al. (1989) and Crawford (1989, 1990).

Optical polarization observations towards NGC 6231 reveal a complex pattern in the angles of the polarimetric vectors (Feinstein et al. 2003). These authors suggest that a supernova explosion may be responsible for the observed orientations.

The bright HII region seen northwest of NGC 6231 in Figure 1 is IC 4628 (see also Figure 7), originally discovered by E.E. Barnard, and also known as Gum 56 (Gum 1955). Crampton & Thackeray (1971) suggested that the HII region is excited by HD 322417, which they classified as an O5.5 star; Walborn (1982) classifies it as an O6 III star, but suggests that it is probably more distant than the Sco OB1 association. IC

4628 was observed at 5000 MHz by Goss & Shaver (1970) and at 408 MHz by Shaver & Goss (1970). Laval (1972) studied the kinematics of the region using Fabry-Perot observations. King (1987) noted that a small globule about 1 degree south-west of IC 4628 is associated with the IRAS source 16509–4049, which appears to be a young star born in the globule. The region is likely to harbor a population of young low-mass stars, and deserves further study.

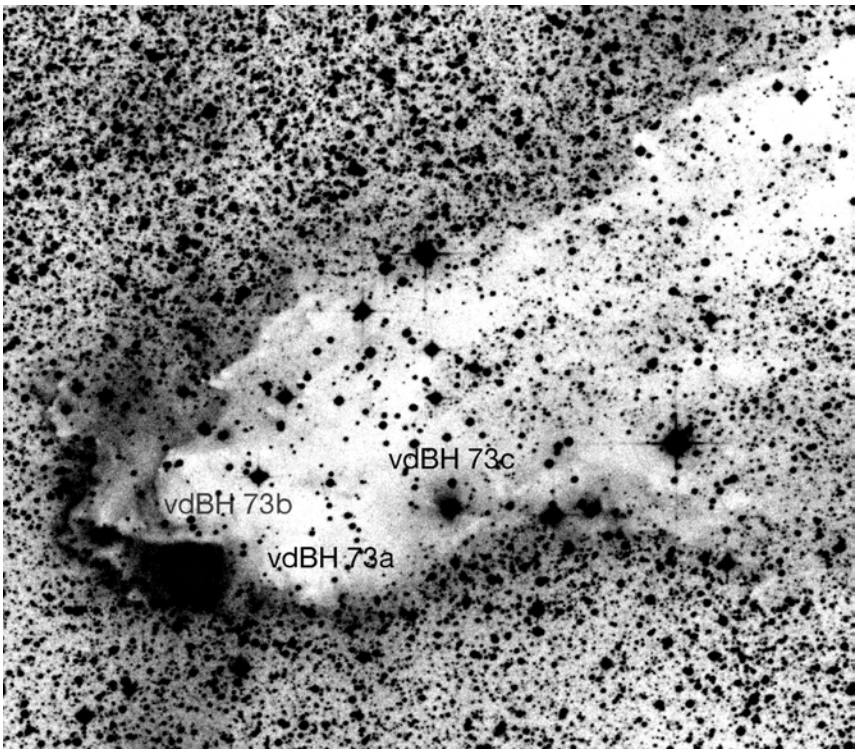

Figure 8. The Large Elephant Trunk pointing towards NGC 6231 as seen on a red Schmidt plate from the UKSTU survey. The figure is 20 arcmin wide.

6. The Large Elephant Trunk

In their description of the Gum 55 region seen in Figure 1, Bok, Bok, & Graham (1966) note: *"A particularly interesting feature ... is the prominent 'elephant trunk' absorption lane which points directly to the cluster, nearly a degree to the east of it."*

van den Bergh & Herbst (1975) identified five reflection nebulae in the Large Elephant Trunk (LET) (improved coordinates are given by Rousseau & Périé 1996). Herbst (1975) gave further photometric and spectroscopic information. Three of the five reflection nebulae, vdBH 73a,b,c, are marked in Figure 8, the two other objects turn out to not be nebulous when examined on more recent sky surveys. Herbst (1975) found that vdBH 73a, which is the largest and brightest reflection nebula, is illuminated by a B2V star CPD $-41^\circ 7613$. It appears that the ionizing radiation and expanding HII

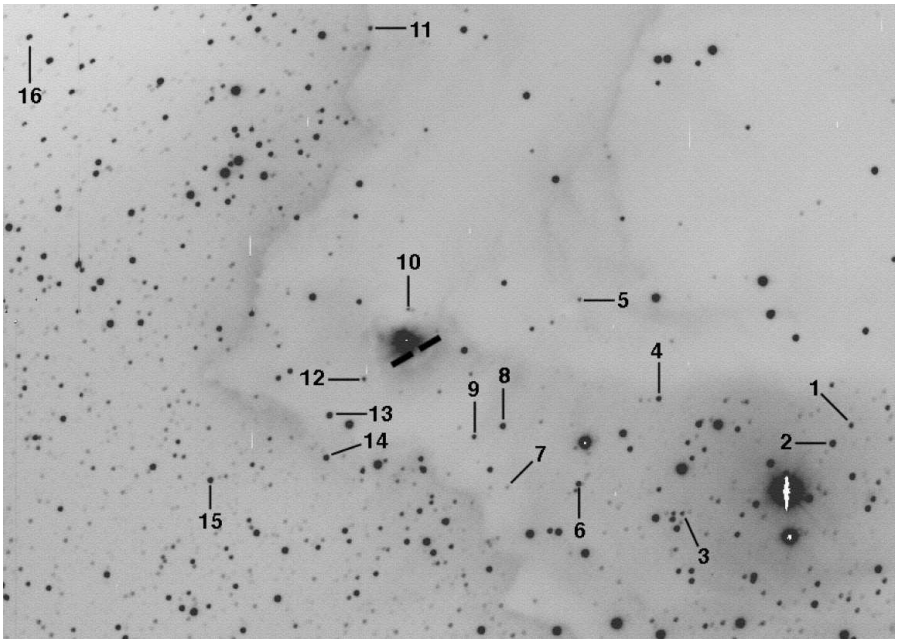

Figure 9. Low-luminosity Hα emission line stars associated with the tip of the Large Elephant Trunk. The bar indicates the location of IRAS 16438−4110, probably associated with the bright Hα emission star BRC 82-10 that is surrounded by the reflection nebula vdBH73b. From Ogura et al. (2002).

Table 1. Hα Emission Stars in the Large Elephant Trunk (after Ogura et al. 2002)

Star	α_{2000}	δ_{2000}	EW[a]	2MASS[b]	J	H	K
BRC82-1	16:47:08.3	–41:16:10	14.7	16470820-4116090	14.46	13.32	12.60
BRC82-2	16:47:08.8	–41:16:16	1.5	16470876-4116153	13.68	12.73	12.26
BRC82-3	16:47:13.4	–41:16:41	93.7	16471358-4116414	14.00	11.68	11.15
BRC82-4	16:47:14.1	–41:16:01	1.5	16471403-4116004	12.91	11.68	11.17
BRC82-5	16:47:16.5	–41:15:28	s	16471646-4115266	15.38	14.19	13.31
BRC82-6	16:47:16.5	–41:16:31	3.0	16471645-4116300	14.07	13.07	12.64
BRC82-7	16:47:18.7	–41:16:32	11.3	16471862-4116313	15.81	14.68	13.96
BRC82-8	16:47:18.8	–41:16;11	0.4	16471876-4116103	14.01	13.14	12.80
BRC82-9	16:47:19.7	–41:16:15	4.9	16471963-4116140	14.95	14.04	13.74
BRC82-10	16:47:21.7	–41:15:31	16.4:	16472157-4115308	15.39	15.00	14.13
BRC82-11	16:47:23.1	–41:13:55	s	16472291-4113542	15.09	13.99	13.24
BRC82-12	16:47:23.1	–41:15:55	14.2	16472304-4115543	14.06	12.66	11.96
BRC82-13	16:47:24.1	–41:16:08	0.9	16472405-4116071	13.69	12.84	12.53
BRC82-14	16:47:24.2	–41:16:22	w	16472414-4116217	14.07	13.24	13.00
BRC82-15	16:47:27.7	–41:16:30	30.3	16472767-4116297	14.36	13.38	12.76
BRC82-16	16:47:33.3	–41:13:59	1.1	16473328-4113584	13.69	12.82	12.41

a: Equivalent width of Hα emission. s = strong, w = weak.

b: All 2MASS sources are closer than 2.2 arcsec to the position of the Hα emission star

region due to NGC 6231 has not only sculpted the LET, but also triggered a second generation of star formation.

Sherwood & Dachs (1976) performed a photometric study of stars in the Sco OB1 association and found support for the suggestion by Bok et al. (1966) that the LET is associated with the NGC 6231 cluster. Blair et al. (1975) detected strong CO emission from the LET at V_{lsr} = –25.3 km/sec, similar to the gas in the NGC 6231 region.

In a study of centimeter radio continuum emission from bright-rimmed clouds, Thompson et al. (2004) detected two 13 and 20 cm sources associated with the tip of the Large Elephant Trunk (their sources SFO 82a and b). Such measurements can help to measure the physical conditions in the ionized boundary layers of the clouds.

Ogura et al. (2002) performed an objective prism survey of the LET, labeled BRC 82 in their nomenclature. They found 16 faint Hα emission stars associated with the head of the cloud (see Fig. 9 and Table 1). These are undoubtedly the low-mass young stars that should co-exist with the more massive stars seen in the cloud and more easily identified by their reflection nebulae.

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