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Triggered Star Formation in the Sco OB2 Association

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Abstract. We explore the star formation history of the Upper Scorpius OB association, the youngest part of large Sco OB2 association. After an initial wide field (160 square-degree) survey for solar-mass pre-main sequence (PMS) stars in Upper Scorpius, we have performed a deeper survey for low-mass ($\sim 0.1 - 0.7\,M_{\odot}$) PMS stars, covering a 6 square-degree area. Our current PMS sample contains nearly 200 stars. In a detailed analysis of the locations of these stars in the HR diagram, taking proper account of the uncertainties and the effects of unresolved binaries, we find a mean stellar age of about 5 Myr and no evidence for a significant age dispersion among these stars. This implies that the star formation history of the Upper Scorpius association was dominated by a short star-burst, which started about 5 Myr ago and ended probably not more than one or two Myr later. This result strongly suggests that the shock wave of a supernova explosion in the nearby Upper Centaurus-Lupus association, that crossed Upper Scorpius just about 5 Myr ago, triggered the star-burst in Upper Scorpius.

1. Introduction

The population of low-mass ($M_{\star} \leq 2\,M_{\odot}$) pre-main sequence (PMS) stars in OB associations can give us important information on the nature of the star formation process. For many years it was thought that star formation is a bimodal process, i.e. that high- and low-mass stars form by different processes (e.g. Larson 1986; Shu & Lizano 1988). This should lead to distinct formation sites for high-mass stars (the OB associations) and low-mass stars (the T-associations). However, it has also been known for a long time that at least some T associations do contain high-mass stars (e.g. Walter & Boyd 1991) and also that OB associations do contain low-mass stars (e.g. Herbig 1962). Thus, the bimodal star formation concept cannot be strictly correct. Nevertheless, there have been

many indications that high-mass star forming regions (most notably starburst regions; cf. Leitherer 1998) contain much smaller numbers of low-mass stars than expected from the field IMF (see discussion in Zinnecker et al. 1993).

Another interesting aspect of OB associations is the presence of numerous massive stars, that creates physical conditions that are very different from those in low-mass star forming regions. In the immediate neighborhood of the massive stars, their ionizing radiation, their stellar winds, and finally their supernova explosions tend to disrupt the parental molecular cloud. At somewhat larger distances, however, the shock waves caused by stellar winds and supernova explosions can induce collapse of molecular cloud cores and thus initiate the star formation process, if the right conditions are met (see Section 5). Thus the comparison of the stellar content and the star-formation history of OB associations to those of low-mass star forming regions lacking massive stars, like the Taurus-Auriga T association, can yield important information about the influence of massive stars on the star formation process.

2. The Sco OB2 association

At a distance of only ~ 140 pc, the Scorpius-Centaurus (Sco-Cen) association is the OB association nearest to the Sun. It contains several hundred B stars which concentrate in the three subgroups Upper Sco (the youngest subgroup), Upper Centaurus Lupus (the oldest subgroup), and Lower Centaurus Crux (cf. de Zeeuw et al. 1999). The area is essentially free of dense gas and dust clouds, probably the consequence of the massive stellar winds and several supernova explosions, which have cleared the region from diffuse matter and created a huge system of loop-like H I structures around the association (cf. de Geus 1992). The winds and supernova explosions from the massive stars in Sco-Cen also created a huge bubble of hot gas, that constitutes the largest structure visible on the sky in X-ray and radio wavelengths.

The Sco-Cen association was very well investigated by the astrometry satellite Hipparcos. De Zeeuw et al. (1999) could identify 120 members to Upper Sco by their space motions. From this study, the population of high-mass ($M_* \gtrsim 3\,M_\odot$) members of Upper Sco is completely known. Furthermore, the ages of these high-mass members are also well known: De Zeeuw & Brand (1985) and de Geus et al. (1989) independently derived an age of 5–6 Myr for the population of B stars in Upper Sco and found no evidence for a significant age spread among these stars.

3. The low-mass stellar population of Upper Sco

While the population of high-mass stars in Upper Sco is well known and investigated, not much was known about the low-mass members until recently. In order to identify a statistically unbiased sample of low-mass members, we therefore have performed a systematic search for PMS stars in Upper Sco. Extending previous investigations of small parts of Upper Sco by Walter et al. (1994) and Kunkel et al. (2000), we have surveyed an area of 160 square-degrees, covering the full extent of the association. By follow-up observations of ROSAT All Sky Survey X-ray sources we were able to identify numerous new PMS stars by

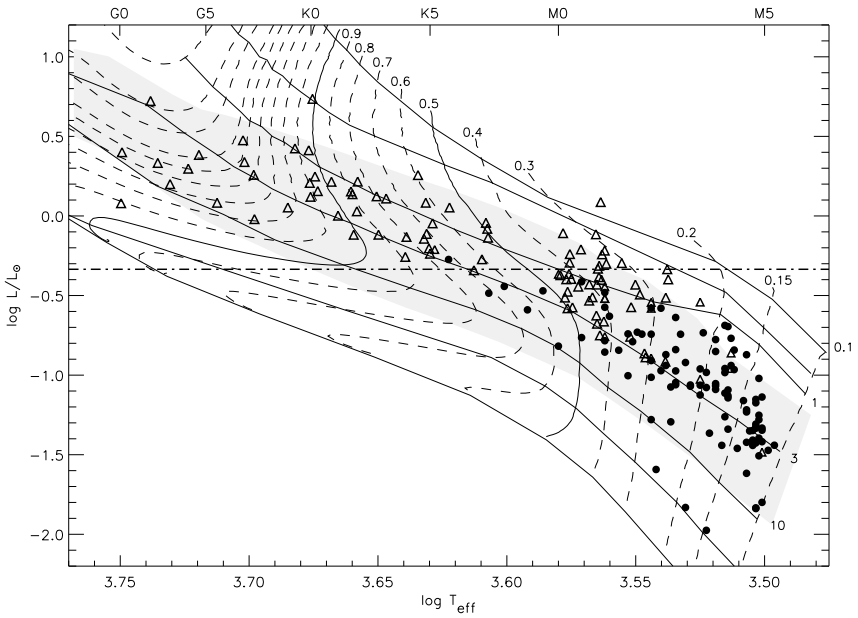

Figure 1. HR diagram for the Upper Sco PMS stars compared to the PMS model of D'Antona & Mazzitelli (1994). The grey shaded band shows the region in which we expect 90% of the PMS stars to lie, based on the assumption of a common age of 5 Myr for all stars and taking proper account of the uncertainties and the effects of unresolved binaries (see Preibisch & Zinnecker 1999 and Preibisch et al. 2001).

their strong lithium absorption lines (for all details see Preibisch et al. 1998). In Preibisch & Zinnecker (1999) we investigated the age distribution of these stars. The next step of our project was a large survey for low-mass PMS stars in Upper Sco. Utilizing the multi-object spectrograph 2dF at the 4 m Anglo-Australian-Telescope, we recently obtained spectra of 576 stars in the magnitude range $R = 12.5 - 16.5$ in a 6 square-degree area in Upper Sco (for details see Preibisch et al. 2001). Among these objects we were able to identify ~ 100 new PMS stars, nearly all of them M-type stars, by their strong Li absorption lines.

Our two surveys increased the number of known PMS stars in Upper Sco to nearly 200 objects. Following the optical characterization of these stars, we have placed them into the HR diagram (Fig. 1). The usual way to interpret such a HR diagram is to derive the mass and age of each star from its location in the diagram by comparison with PMS models. However, any measurement errors like uncertainties in the photometry or a spread of individual stellar distances, will cause errors in the derived stellar masses and ages. Another important problem is that the ages derived from the position in the HR diagram will systematically underestimate the true ages because of the presence of unresolved binary systems.

We thus decided to use a different approach for our study of the age structure of the association. As described in detail in Preibisch & Zinnecker (1999), we simulated the location of the members of a model star cluster with a given age distribution in the HR diagram, taking proper account of the sources of errors mentioned above. The resulting region in the HR diagram can then be

compared to the observed location of the stars and tell us whether the underlying assumptions are consistent with the observations or not. We find (see Fig. 1) that the location of the PMS stars in the HR diagram is fully consistent with a model assuming that all stars have an age of 5 Myr. This mean age of the low-mass stars agrees very well with the age of 5–6 Myr previously found for the massive stars and shows that low-mass and high-mass stars are coeval and co-spatial and thus probably have formed together. The absence of a significant age dispersion (our modeling suggests that the spread in stellar ages is smaller than about 2 Myr) implies that all stars in the association have formed more or less simultaneously. This means that the star-formation process must have started rather suddenly and at the same time everywhere in the association, and also must have ended rather suddenly after at most a few Myr. The star formation process in Upper Sco thus can be considered as a relatively short burst of high star formation activity. This scenario calls for some kind of external trigger that initiated the star burst in Upper Sco and some mechanism that terminated the star burst shortly thereafter. We believe that both effects were caused by massive stars.

4. The impact of massive stars on their environment

Massive stars, upwards of about ten solar masses, profoundly affect their environment in several ways (e.g. Garay & Lizano 1999). O-type stars emit *intense UV radiation* that ionizes and heats the surrounding material and can profoundly affect nearby cloud cores and the circumstellar material around young stellar objects by photoevaporation as can be nicely seen at the proplyds in the Trapezium cluster (Bally et al. 1998; see also Richling & Yorke 1998; 2000). The *powerful winds* of massive stars deposit considerable amounts of momentum and kinetic energy into their surrounding medium. For example, a single O5 star is perfectly capable of dispersing a $10^4\,M_\odot$ molecular cloud completely within only about 1 Myr (cf. Yorke 1986). Finally, after a few Myr, the most massive ($\gtrsim 10\,M_\odot$) stars end their life with *supernova explosions*. Each supernova causes a strong shock wave that expands with initial velocities of $\gtrsim 10\,000$ km/sec and transfers typically some 10^{51} erg of kinetic energy in the ambient interstellar medium.

In the vicinity of the massive stars, the effect of their action is certainly devasting. As soon as the first O-star 'ignites', it will terminate the star formation process in a steadily increasing volume around it. At larger distances, however, the slowed-down shock waves driven by massive stellar winds and/or supernova explosions can provide the compression necessary to initiate cloud collapse and to induce star formation.

5. Triggered star formation

Several recent numerical studies have dealt with the problem of a shock wave traveling through a molecular cloud and hitting cloud cores (e.g. Boss 1995; Foster & Boss 1996, 1997; Vanhala & Cameron 1998; Fukuda & Hanawa 2000). These studies found that the outcome of the impact of the shock wave on the cloud core mainly depends on the shock velocity: if the shock wave is faster

than about 50 km/sec, the cloud core is shredded to pieces. If the shock wave is slower than about 10 km/sec, it causes only a slight temporary compression of the core. Shock waves with velocities in the range of $\sim 10-45$ km/sec, however, are able to induce collapse of molecular cloud cores.

A potential source of shock waves with velocities in that range are relatively distant supernova explosions. The supernova must neither be too close to the core (because then the shock wave will be too fast and destroy the core) nor too far away from the core (because then the shock wave will be too slow to trigger collapse). The appropriate range of velocities that are suitable to trigger molecular cloud core collapse roughly translates into a range of distances between 10 pc and 100 pc, the exact values obviously depending strongly on the details of the cloud structure and the evolutionary state of the pre-impact core. Other potential sources of shock waves with velocities in the desired range include wind-blown bubbles, expanding H II regions, and novae. Another interesting source of shock waves with typical velocities of a few tens of km/sec are protostellar outflows. Once a burst of star forming activity is started in a molecular cloud, e.g. triggered by a supernova shock wave, many of the forming stars will produce protostellar outflows and some of these outflows will hit other cloud cores and can be expected to drive them into collapse. This might provide a positive feedback to the star formation process and increase the star formation activity even further.

Several examples for triggered star formation have been discussed in the literature. For example, it has been suggested that star formation in the CMa R1 association (cf. Herbst & Assousa 1977) as well as the Cep OB3 association (cf. Assousa et al. 1977) has been triggered by expanding supernova shells. Oey & Massey (1995) discuss the dynamics of the superbubble H II region DEM 152 in the LMC and find evidence for triggered star formation. In the Cone nebula the formation of six young stellar objects is thought to be triggered by the wind from a B2 star at the center of the system (cf. Thompson et al. 1998). A good example of the positive feedback on the star forming activity provided by numerous protostellar outflows might be the NGC 1333 star forming region (Sandell & Knee 2000). On larger scales, evidence for triggered star formation has been found in the 30 Doradus Nebula by Rubio et al. (1998) and Walborn et al. (1999). Their results suggest that a new stellar generation is being triggered by the energetic activity of the massive central cluster in the remnant interstellar material around its periphery. Walter & Brinks (1999) found evidence for propagating star formation in the nearby dwarf galaxy IC 2574. The star formation activity is concentrated along the rims of expanding H I shells, which can be understood in terms of the combined effects of stellar winds and multiple supernova explosions.

6. The triggered star burst in Upper Sco

In Section 3 we concluded that the star burst in Upper Sco was probably triggered by some external effect. Interestingly, a suitable trigger is actually available and this allows us to draw a nice and consistent picture of the star formation history of Upper Sco (see also Preibisch & Zinnecker 1999). As mentioned above, the Sco-Cen association is surrounded by several large H I loops, which were cre-

ated by supernova explosions and stellar winds. The kinematic properties of the largest and thus oldest of these shells ($v \sim 10$ km/sec, radius ~ 110 pc) suggest that it was created by a supernova explosion in the Upper Centaurus-Lupus association about 12 Myr ago. The geometric and kinematic data suggest that this shock wave passed through the former Upper Sco molecular cloud just about 5–6 Myr ago (de Geus 1992). This point in time agrees very well with the stellar ages of the low-mass stars as well as the high-mass stars in Upper Sco, that have been determined in an absolutely independent way. Furthermore, since the distance from Upper Centaurus-Lupus to Upper Sco is about 50 pc, this shock wave probably had precisely the properties that are required to induce star formation according to the modeling results mentioned above. Thus, the assumption that this supernova shock wave triggered the star formation process in Upper Sco provides a self-consistent explanation of all observational data.

During the star burst, probably more than 1000 stars formed within a period of at most 1–2 Myr. This suggests that there was a very large number (several hundreds) of protostellar outflows that might well have triggered further cloud collapse and accelerated the star formation rate. However, these outflows presumably also initiated the disruption of the molecular cloud. Cloud dispersion must have increased strongly after a few 10^5 years, when the new-born massive stars "turned on" and started to affect the cloud by their ionizing radiation and their strong stellar winds. The combined effect of numerous massive stars affected the cloud so strongly that after a period of $\lesssim 1$ Myr the star formation process was terminated, simply because all the remaining cloud material had been disrupted. This explains the narrow age distribution, i.e. the lack of stars that formed later than $\gtrsim 1$ Myr after the onset of the starburst.

Finally, we note that the most massive star in Upper Sco (presumably a $40\,M_\odot$ star; cf. de Geus 1992) exploded as a supernova about 1.5 Myr ago. The shock wave of this explosion fully dispersed the remnant cloud material in Upper Sco, and must have reached the ρ Oph cloud within the last 1 Myr. Interestingly, the ρ Oph cloud actually shows evidence for compression from the rear south-western side and for the presence of a slow shock (cf. Motte et al. 1998). It might well be that this shock wave now triggers the current burst of star formation in the ρ Oph cloud. In summary, we conclude that the Sco-Cen OB association constitutes one of the best examples of triggered star formation.

References

D'Antona, F., & Mazzitelli, I. 1994, ApJS, 90, 467

Assousa, G.E., Herbst, W., Turner, K.C. 1977, ApJ, 218, L13

Bally, J., Sutherland, R.S., Devine, D., Johnstone, D. 1998, AJ, 116, 293

Boss, A.P. 1995, ApJ, 439, 224

Brown, A.G.A., Blaauw, A., Hoogerwerf, R., de Bruijne, J.H.J., & de Zeeuw, P.T. 199, in The Origin of Stars and Planetary Systems, ed. C.J. Lada & N.D. Kylafis (Kluwer Academic Publishers), 411

de Geus, E.J. 1992, A&A, 262, 258

de Geus, E.J., de Zeeuw, P.T., & Lub, J. 1989, A&A, 216, 44

Foster, P.N., & Boss, A.P. 1996, ApJ, 468, 784

Foster, P.N., & Boss, A.P. 1997, ApJ, 498, 346

Fukuda, N., & Hanawa, T. 2000, ApJ, 533, 911

Garay, G. & Lizano, S. 1999, PASP, 111, 1049

Herbig, G.H. 1962, Adv. Astron. Astrophys., 1, 47

Herbst, W., & Assousa, G.E. 1977, ApJ, 217, 473

Kunkel, M., Brandner, W., Yorke, H.W., et al. 2000, ApJS, submitted

Larson, R.B. 1986, MNRAS 218, 409

Leitherer C. 1998, in ASP Conf. Ser. Vol. 142, The Stellar Initial Mass Function, ed. G. Gilmore & D. Howell (San Francisco: ASP), 45

Motte, F., André, P., & Neri, R. 1998, A&A, 336, 150

Oey, M.S. & Massey, P. 1995, ApJ, 452, 210

Preibisch, Th., & Zinnecker, H. 1999, AJ, 117, 2381

Preibisch, Th., Guenther, E., Zinnecker, H., Sterzik, M., Frink, S., & Röser, S. 1998, A&A, 333, 619

Preibisch, Th., Guenther, E., & Zinnecker, H. 2001, AJ, in press, (available at: `http://www.mpifr-bonn.mpg.de/staff/tpreibis/publications.html`)

Richling, S. & Yorke, H.W. 1998, A&A, 340, 408

Richling, S. & Yorke, H.W. 2000, ApJ, 539, 258

Rubio, M., Barba, R.H., Walborn, N.R., Probst, R.G., Garcia, J., & Roth, M. 1998, AJ, 116, 1708

Sandell, G., & Knee, L.B.G. 2000, ApJL, in press

Shu F.H., & Lizano S. 1988, in Stellar Matter, ed. J.M. Moran & P.T.P. Ho (Gordon & Breach), 65

Thompson, R.I., Corbin, M.R., Young, E., & Schneider, G. 1998, ApJ, 492, L177

Vanhala, H. A. T & Cameron, A. G. W. 1998, ApJ, 508, 291

Walborn, N.R., Barba, R.H., Brandner, W., Rubio, M., Grebel, E.K., & Probst, R.G. 1999, AJ 117, 225

Walter, F.M., & Boyd, W.T. 1991, ApJ, 370, 318

Walter, F., & Brinks, E. 1999, AJ, 118, 273

Walter, F.M., Vrba, F.J., Mathieu, R.D., Brown, A., & Myers, P.C. 1994, AJ, 107, 692

Yorke, H.W. 1986, ARAA, 24, 49

de Zeeuw, P.T., & Brand, J. 1985, in Birth and Evolution of Massive Stars and Stellar Groups, ed. H. van den Woerden & W. Boland (Dordrecht: Reidel), 95

de Zeeuw, P.T., Hoogerwerf, R., de Bruijne, J.H.J., Brown, A.G.A., & Blaauw, A. 1999, AJ, 117, 354

Zinnecker, H., McCaughrean, M.J., & Wilking, B.A. 1993, in Protostars and Planets III, ed. E.H. Levy & J.I. Lumine (Tucson: University of Arizona Press), 429