KINEMATIC EVIDENCE FOR PROPAGATING STAR FORMATION INDUCED BY OB ASSOCIATIONS

F. Comerón[1], **J. Torra**[2], **A.E. Gómez**[3], **C. Jordi**[2]
[1]European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching bei München, Germany
[2]Departament d'Astronomia i Meteorologia, Universitat de Barcelona, E-08028 Barcelona, Spain
[3]DASGAL, Observatoire de Meudon, F-92195 Meudon Cedex, France

ABSTRACT

We report the detection of expanding patterns, revealed by Hipparcos proper motions, in some OB associations. The expansion velocities exceed typical internal motions in associations, and suggest that very energetic processes may have been responsible for both the formation of the stars and their initial velocities. Observations of related interstellar gas support this explanation. One of the regions is located near the Cygnus Superbubble, a large X-ray emitting cavity centered on the Cygnus OB2 association. Stars in this region seem to be expanding away from the center of the Superbubble, and the Hipparcos data allow to trace the expanding pattern all over the area of the Superbubble. The other expanding pattern is in Canis Major, with the stars of Canis Major OB1 mostly lying between the center of expansion and the Canis Major R1 association, where star formation is taking place at present.

We propose that the OB stars in Cygnus formed as a consequence of gravitational instabilities in a dense shell surrounding the Cygnus Superbubble, which in turn is a byproduct of the activity of the massive stars of Cygnus OB2. For Canis Major OB1, star formation may have been triggered by a supernova explosion near a dense molecular cloud. This is supported by the existence of a new runaway star, HIP 35707, moving away from the center of expansion, which may have been the binary companion of the supernova progenitor, released after the explosion.

Key words: early-type stars; star formation; OB associations.

1. INTRODUCTION

Propagating star formation, in which the energetic activity of massive stars compresses the surrounding gas and triggers the formation of new generations of stars, is thought to be a common process in spiral and irregular galaxies. Observational evidence for its existence can be found at different scales (Elmegreen 1992), and it is usually inferred from the spatial arrangement of stars, age gradients, or signs of the interaction between the stars and the gas.

It may be also expected that the same energetic output of the massive stars could induce large scale motions in the surrounding gas, and that these motions may be reflected in the velocities of the new generations of stars formed in this way. Kinematic evidence for star formation is nevertheless elusive: simple energetic considerations make it easy to see that these velocities should be at most of order of some km s^{-1}. However, the quality of Hipparcos proper motions may enable us to reach the required level of precision for stars located within distances of the order of $1-2$ kpc. Given the considerable number of OB associations located within this radius from the Sun, it seems therefore worthwhile to carefully examine the motions of their member stars, to investigate the possibility that some regions may show bulk motions indicative of propagating star formation.

The main results of this work have been the confirmation of a large scale expansion in Cygnus, already suspected from ground-based observations, as well as the discovery of a similar pattern in the Canis Major region. The main features of these regions are discussed in this paper, as well as their possible origin. A more in-depth description of these results and the models used to interpreted them can be found elsewhere (Comerón et al. 1997).

2. THE STELLAR SAMPLE

The database used for this study is composed of stars from the proposal *Young stars: irregularities of the velocity field and spiral structure*, by M.O. Mennessier. The global sample consists of 6290 O and B stars. Since our main interest lies in the motions of groups of young stars beyond the local system, dominated by the Gould Belt (Comerón et al. 1994, Lindblad et al. 1997), we excluded from our sample stars with measured trigonometric parallax greater than 3 mas, as well as those over 5° from the galactic equator. We further retained only stars with spectral type B2 or earlier for luminosity classes IV and V, B4 or earlier for classes II and III, and all the O and B supergiants. The so-defined sample contains 1092 stars, with proper motions typically accurate to

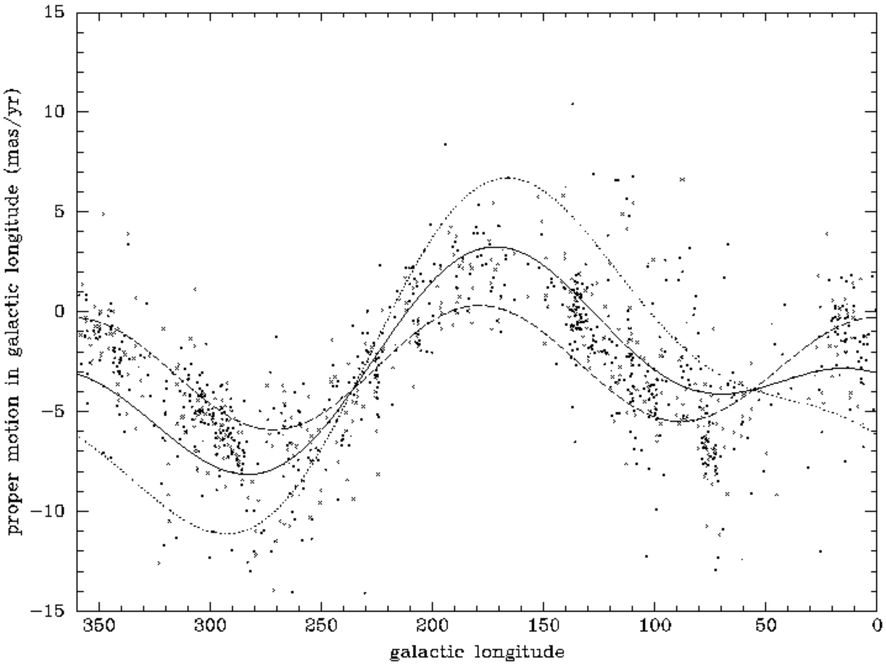

Figure 1. Distribution of stars in galactic longitude versus proper motion in galactic longitude. The lines represent the systematic proper motions expected from the circular galactic rotation and the solar peculiar velocity for stars located at different distances from the Sun: d = 0.5 kpc (dotted line), d = 1 kpc (solid line) and d = ∞ (dashed line). The latter represents the motions of distant stars for which the reflection of the solar motion (decreasing as 1/d) is insignificant as compared to the galactic rotation (independent of d). It is assumed that all the stars are nearby enough so that the first order approximation to the galactic rotation curve is valid.

within 0.8 mas yr^{-1}. Hipparcos parallaxes for most of these stars are well below their standard error.

3. THE CYGNUS REGION

Large-scale anomalous proper motions of O and B stars in Cygnus were already reported by Comerón et al. (1993). That study used Hipparcos Input Catalogue data to show that stars in the area occupied by the associations Cygnus OB1, OB3, and OB9 move with a velocity deviating by a few tens of km s^{-1} from that expected due to the galactic rotation and solar motion alone. The anomalous motions appeared as a clump of stars in the galactic longitude (l) versus proper motion in galactic longitude (μ_l) diagram, lying clearly below the curve describing the systematic effects due to galactic rotation and solar motion.

The Hipparcos data for our sample of stars reveal that clump much more clearly, as can be seen in Figure 1. Shown in the figure is the distribution of stars in l and μ_l, and three curves describing the systematic proper motion expected for stars located at 500 pc, 1 kpc, and infinite distance from the Sun. In practise, the last curve refers to stars distant enough so that the reflected solar peculiar velocity in their proper motions is negligible. A first-order approximation to the galactic rotation has been used (e.g. Scheffler & Elsässer 1987), with Oort constants corresponding to a flat rotation curve, $A = -B = 13$ km s^{-1} kpc^{-1}. The adopted solar motion is $(7.4, 15.3)$ km s^{-1} in the direction of the galactic center and the galactic rotation, respectively (Comerón et al. 1994). Most of the stars are located between the curves $d = 500$ pc and $d = \infty$, as could be expected from our selection criteria. Clusters of points at some intervals of l can be identified with individual associations or with fragments of spiral arms. The anomalous motions in Cygnus are represented by the cluster of points centered near $(l, \mu_l) = (75°, -7$ mas yr$^{-1})$: this cluster falls in a *forbidden* region of the $l - \mu_l$ diagram, where no stars should lie according to the kinematical model used here, regardless of their distance. This feature is nearly insensitive to reasonable changes in the adopted parameters describing the solar motion and galactic rotation.

The location of the anomalously moving OB associations in the vicinity of the Cygnus Superbubble was noted by Comerón et al. (1993), as well as the fact that their motion is directed away from the center of the Superbubble. The Superbubble was discovered in the X-ray sky survey carried out by the Einstein satellite (Cash et al. 1980) and, although its reality as a single entity was initially put in doubt (Bochkarev & Sitnik 1985), recent images from the ROSAT all-sky survey clearly show it as a coherent, well-defined extended structure (MPE 1995). X-ray emitting superbubbles have been studied in the Milky Way and some nearby galaxies (Tenorio-Tagle & Bodenheimer 1988, Chu & Mac Low 1990, Chu 1994), and are usually associated with recent supernovae or with associations containing large numbers of OB stars, able to inject a large mechanical power into their surround-

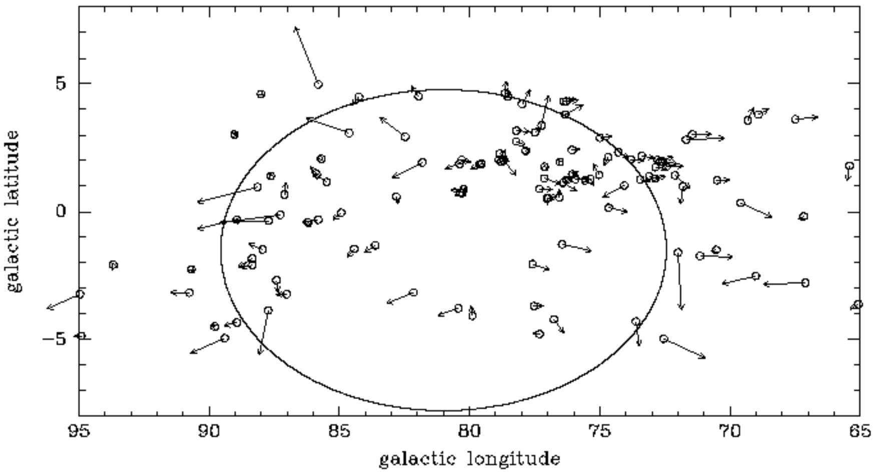

Figure 2. Positions and velocities of stars in the Cygnus region. The arrows represent residual motions in the plane of the sky, after subtraction of the adopted systematic motions, and assuming a distance of 1250 pc. The largest residual motion represented corresponds to the star at $l = 85^\circ\!.81$, $b = 4^\circ\!.98$, *and is 9.8 mas* yr^{-1}. *The ellipse represents the approximate outer limits of the Cygnus Superbubble.*

ings. This is also the case of the Cygnus Superbubble, near whose center lies Cygnus OB2, a very rich and compact association containing some of the brightest massive stars in the Milky Way (Torres-Dodgen et al. 1991, Massey & Thompson 1991, Massey et al. 1995). Studies of the structure and evolution of the Cygnus Superbubble have been carried out by Abbott et al. (1981) and Bochkarev & Sitnik (1985). Another outstanding structure in the same region is the Cygnus X molecular complex (Wendker et al. 1991 and references therein). An overall review of star forming regions in Cygnus can be found in Odenwald & Schwartz (1993).

The overall pattern of proper motions in Cygnus is shown in Figure 2, superimposed on an outline of the Superbubble contour. The arrows show the residual proper motion, after subtraction of the systematic contributions of the solar motion and the galactic rotation, using the parameters described at the beginning of this Section. The average distance used to remove the systematic component is $d = 1250$ pc (Comerón et al. 1993). It is clear from Figure 2 that not only the associations previously studied by Comerón et al. (1993) move away from the center of the Superbubble: stars lying in other areas of the Superbubble also do the same. In particular, this is so for the stars lying in the western part of the Superbubble, which belong to the sparse association Cygnus OB7. The expanding pattern can thus be traced all along the perimeter of the Superbubble with the new Hipparcos data.

It is important to wonder whether the stars presumably forming this structure are all at similar distances from the Sun. Unfortunately, as mentioned in Section 2, their trigonometric parallaxes are too small for Hipparcos. On the other hand, distances based on spectral classification and BV photometry are very uncertain: one of the reasons is the difficulty of calibrating the upper part of the H-R diagram (the same applies to distance estimates based on narrow-band photometry; see discussion in Comerón et al. 1993). The calibration is nevertheless likely to be substantially improved by Hipparcos, and it can thus be expected that Hipparcos will provide indirect, but highly valuable information on the distances to these stars. Another difficulty comes from the large extinction along the line of sight to the stars of interest, and the consequent errors derived from an uncertain and/or variable total-to-selective extinction ratio (Terranegra et al. 1994). Some discussion on these effects can be found in Comerón et al. (1997).

The motions of Cygnus OB1, OB3, and OB9 were explained by Comerón & Torra (1994) assuming that the associations formed from gravitational instabilities in a shell surrounding the Superbubble. Related work has been done by McCray & Kafatos (1987) and Elmegreen (1994). The outline of the process is as follows: about 10^7 years ago, the oldest massive stars in Cygnus OB2 formed. The interaction of their winds with the surrounding medium produced a high pressure bubble of hot gas, along the ways described by Weaver et al. (1977). The expansion of the bubble took place with a highly supersonic velocity at the beginning, and the shocked ambient gas was heated to very high temperatures and incorporated into the bubble interior. However, as the expansion progressed and deccelerated, the cooling time of the shocked ambient gas eventually became smaller than the expansion timescale of the bubble; at that point, a dense shell began to form around the bubble. With time, the growing surface density and radius of this shell could trap inside it the ionizing flux of the stars of the association, turning off the main heating mechanism in the outer part of the shell. The shell thus became colder and denser and, as the expansion progressed, it eventually became unstable against its own gravity.

The model developed by Comerón & Torra (1994) assumed that the presently observed stellar motions reflect the expansion velocity of the shell at the onset of the gravitational instability. Under these conditions, Comerón & Torra (1994) showed that the energy injected by the central OB association per unit time, L, is related to the expansion velocity of the stars, V, by:

$$L \simeq 80.8 \frac{c_s}{G} V^4 \qquad (1)$$

where c_s is the effective sound speed in the shell, expected to be around 1 km s^{-1}, and G is the gravitational constant. The observed expansion velocity can thus be used to infer the power injected by the stellar winds and supernovae in the Superbubble. An estimate of the latter quantity can be independently obtained from the presently observed stellar contents of the association. A comparison to the value inferred from Equation 1 should then indicate whether this hypothesis on the origin of the expanding motions in the association is acceptable.

The largest tangential velocities in Cygnus, using the adopted distance, are about 65 km s^{-1}. Replacing this value in Equation 1, one obtains $L = 2.1 \times 10^{41}$ erg s^{-1}, equivalent to one supernova every 150 years. This power is orders of magnitude too large, even for a rich association like Cygnus OB2, and in practice discards the possibility that the fastest observed stars may have been formed by this process.

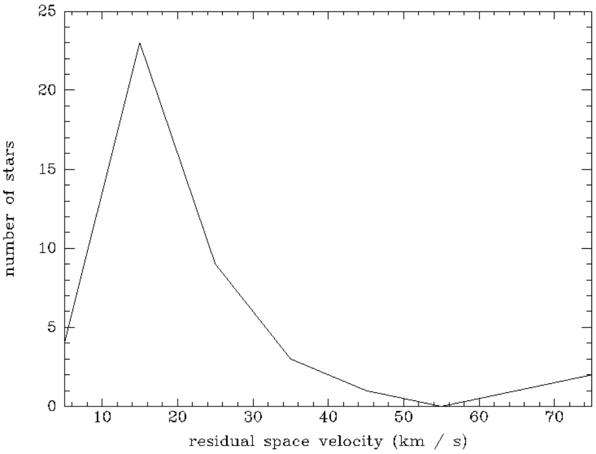

Figure 3. Histogram of space velocities of the stars of our sample having measured radial velocities. The typical uncertainty in the radial velocity is $\sim$ 15 km s^{-1}, about three times larger than in tangential velocity, and this can cause some smear in the bins. However, the gap between the runaways and the rest of the stars is clearly seen.

A closer inspection at the data suggests that the expanding pattern is actually composed by two different populations, with distinct kinematical characteristics and unrelated origins. Shown in Figure 3 is the distribution of residual spatial velocities of the stars that are moving away from the expansion center, with the solar motion and the galactic rotation subtracted. The spatial velocities were calculated using Hipparcos data for the tangential component, and radial velocities from the literature (mostly Evans 1967). The accuracy of the radial velocities is much smaller than that of tangential velocities at the adopted distance, but the radial component is still useful in revealing the gap between the bulk expanding population, peaking around 15 km s^{-1}, and the fastest stars, with velocities exceeding 60 km s^{-1}. The rather long tail of the bulk population, extending up to 50 km s^{-1}, is probably an artifact of the limited quality of the published radial velocities.

We interpret the bulk expanding population as the one produced by the gravitational instability mechanism outlined above, while the stars with velocities in excess of 50 km s^{-1} are probably runaways expelled from Cygnus OB2 itself. Such a population of runaway stars is expected around a rich and dense association like Cygnus OB2, and is not related to the gravitational instability studied here; therefore, to estimate the value of V to be used in Equation 1 for the bulk population, we take the highest observed non-runaway tangential velocities. The use of the tangential velocity alone is justified by the fact, mentioned above, that the tail in the distribution of spatial velocities is likely to be dominated by the large errors in the radial component. We implicitly assume that the largest observed proper motions correspond to stars whose velocities are nearly perpendicular to the line of sight. This is a reasonable assumption, given the large number of stars in the bulk expanding population. In this way, we use $V = 25$ km s^{-1} in Equation 1.

The strong dependence of L on V in Equation 1 dramatically reduces the energetic requirements on Cygnus OB2 when decreasing V from 65 to 25 km s^{-1}. The inferred mechanical power of Cygnus OB2 now becomes $L = 4.7 \times 10^{39}$ erg s^{-1}. This is compatible with the estimated output from its member stars, given the roughness of the approximations involved in deriving Equation 1, in estimating the stellar contents of Cygnus OB2, and in translating it into stellar wind mechanical power. More detailed investigations of Cygnus OB2 in the future may allow a better assessment on the validity of our hypothesis, but the presently available data on the whole region suggest it to be feasible.

4. THE CANIS MAJOR REGION

An overall view of the other region where expansion is detected, Canis Major, is presented in Figure 4. Overlaid dashed contours represent the intensity of the IRAS 100 μm emission. The stars of Canis Major OB1 are scattered over most of the lower half of the area. The molecular gas of the region is concentrated in the southwestern part, and contains several HII regions in addition to the Canis Major R1 association, where star formation is going on at present. Most of the O and B stars seem to be moving away from a point roughly placed at galactic coordinates $(l, b) = (226^{\circ}\!.5, -1^{\circ}\!.6)$, with tangential velocities in the range $10 - 15$ km s^{-1} at the distance of 1150 pc found by Clariá (1974). Figure 4 extends northwards from the association in order to include HIP 35707, whose direction of motion passes very near the center of expansion. The apparent magnitude and spectral type of HIP 35707 place it at the same distance as the stars of Canis Major OB1, implying a tangential velocity of 90 km s^{-1}, characteristic of a runaway star. However, to our knowledge, the runaway nature of HIP 35707 has not been previously recognized.

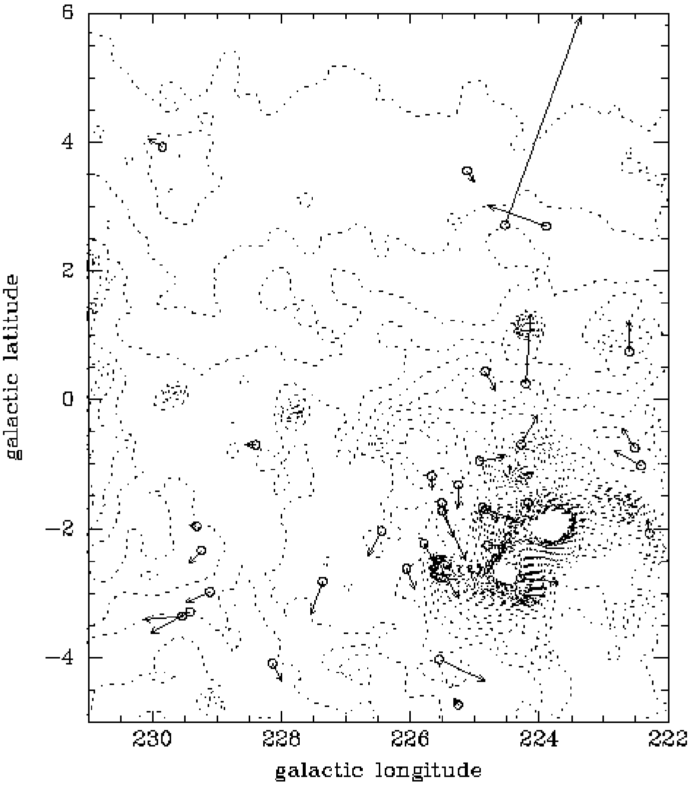

Figure 4. Positions and velocities of stars in the Canis Major region. The arrows represent residual motions in the plane of the sky, after subtraction of systematic motions according to Equation 1. A distance of 1150 pc has been assumed. The dashed lines represent intensity contours of the 100 μm emission detected by IRAS. The main concentration of emission in the southwest contains the HII regions S292, S293, S295, and S296.

It was already suggested by Herbst & Assousa (1977) that star formation in the Canis Major region could have been triggered by a supernova. Those authors suggested the supernova to have been a member of Canis Major OB1, and to have blown a bubble surrounded by a shell much in the same way as an association with stellar winds would do (see e.g. Reynolds (1988) for a discussion of the analogies and differences between wind-blown and supernova shells). Observational evidence for the shell is found in HI position-velocity maps. Star formation in Canis Major R1 by means of magnetogravitational instabilities was further considered by Baierlein et al. (1981) and Baierlein (1983). The expanding motions revealed by Hipparcos support the idea of a very energetic event as the trigger of star formation in the region; the runaway nature of HIP 35707 may be the consequence of the explosion of an originally binary supernova progenitor. The new results suggest that the stars of Canis Major OB1 itself, or at least many of them, were formed as a consequence of that event. Nevertheless, the gravitational instability mechanism proposed in the previous Section for Cygnus cannot account for the patterns observed in this case: first, there is no powerful OB association like Cygnus OB2 in the region, able to provide the high rate of mechanical energy by stellar winds required to produce an unstable shell while still expanding at the velocity of the stars in Canis Major. On the other hand, the shell produced by a single supernova would become gravitationally unstable only at very late stages, when the expansion velocity had fallen well below the observed values.

These requirements could be relaxed if the supernova explosion had taken place near a dense, finite medium on the verge of gravitational collapse, such as a large clump in a molecular complex. The supernova blast would then compress the clump and set it in motion, producing the presently observed stars and their expansion. This may be expected to happen for a very massive star which, at the end of its short lifetime, has not had time to move away from its parental cloud. A part of the cloud would be eroded during the evolution of the star, probably undergoing a *champagne* phase (Tenorio-Tagle 1982, Comerón 1997). The final supernova explosion would then take place inside a partially open cavity surrounded by dense gas, as described by Yorke et al. (1989). With an appropriate combination of mass and size of the cavity, the members of Canis Major OB1, with their measured expansion velocity, could have been formed. From momentum conservation considerations, the mass of a hemispherical shell, M_s, which could be accelerated to a velocity v_s is:

$$M_s \sim \frac{E_{SN}}{v_{ej} v_s} \qquad (2)$$

where $E_{SN} \simeq 10^{51}$ erg is the energy released by the explosion, and $v_{ej} \simeq 10^4$ km s^{-1} is the velocity of the ejecta. For $v_s \simeq 15$ km s^{-1}, M_s turns out to be ~ 300 M$_\odot$. This is probably a conservative estimate, as the remnants of the clump must have started to be accelerated outwards already during the pre-supernova evolution: a more likely value can be $M_s \sim 10^3$ M$_\odot$. This seems to be compatible with the observed stellar contents of the association, although this statement should be confirmed by establishing a more complete census of its members reaching down to smaller masses.

The picture emerging from the above considerations, plus those derived from the arrangement of star forming regions and interstellar matter, is as follows: a binary system of massive stars formed in the northeastern part of a molecular complex in Canis Major several million years ago. The wind and ionizing flux from the system eroded the parental clump and started to move it away, possibly producing a *champagne* flow towards the northeast; this is inferred from the absence of dense gas and stars in that direction. About one million years ago, the most massive component of the system exploded as a supernova; an approximate dating of this event is possible by tracing the path followed by HIP 35707 back to the expansion center. The blast produced the final compression and acceleration of the remnants of the parental clump. Its densest parts collapsed, giving origin to the present members of Canis Major OB1, while the blast wave propagated faster across more tenuous regions. Some $\sim 10^5$ years ago, the blast wave reached another concentration of gas in the southwestern part, the current place of Canis Major R1, starting star formation in it. The average projected speed of the star formation wave can be estimated by dividing the projected distance between the expansion center and Canis Major R1, by the time since the supernova explosion; its value, 60 km s^{-1}, is greater than, but comparable to the expansion velocity of the HI shell measured by Herbst & Assousa (1977). The difference may be accounted for by the continued decceleration of the supernova shell.

ACKNOWLEDGEMENTS

The work of JT and CJ is supported by the CICYT under contract ESP95-0180.

REFERENCES

Abbott, D.C., Bieging, J.H., Churchwell, E., 1981, ApJ, 250, 645.

Baierlein, R., 1983, MNRAS, 205, 669.

Baierlein, R., Schwing, E., Herbst, W., 1981, Icarus, 48, 49.

Bochkarev, N.G., Sitnik, T.G., 1985, Ap&SS, 108, 237.

Cash, W., Charles, P., Bowyer, S., Walter F., Garmire, G., Riegler, G., 1980, ApJ, 238, L71.

Chu, Y.-H., 1994, in 'The soft X-ray cosmos', eds. E.M. Schlegel & R. Petre, American Institute of Physics.

Chu, Y.-H., Mac Low, M.-M., 1990, ApJ, 365, 510.

Clariá, J.J., 1974, A&A, 37, 229.

Comerón, F., 1997, A&A, in press.

Comerón, F., Torra, J., 1994, ApJ, 423, 652.

Comerón, F., Torra, J., Jordi, C., Gómez, A.E., 1993, A&AS, 101, 37.

Comerón, F., Torra, J., Gómez, A.E., 1994, A&A, 286, 789.

Comerón, F., Torra, J., Gómez, A.E., 1997, A&A, submitted.

Elmegreen, B.G., 1992, in 'Evolution of interstellar matter and dynamics of galaxies', eds. J. Palous, P.O. Lindblad, W.B. Burton, Cambridge Univ. Press.

Elmegreen, B.G., 1994, ApJ, 427, 384.

Evans, D.S., 1967, IAU symp, 30, 57.

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

Lindblad, P.O., Palous, J., Lodén, K., Lindegren L., 1997, ESA SP–402, this volume

Massey, P., Thompson, A.B., 1991, AJ, 101, 1408.

Massey, P., Johnson, K.E., DeGioia-Eastwood, K., 1995, ApJ, 454, 151.

McCray, R., Kafatos, M., 1987, ApJ, 317, 190.

MPE, 1995, 5 Jahre ROSAT, Max-Planck-Institut für Extraterrestrische Physik.

Odenwald, S., Schwartz, P.R., 1993, ApJ, 405, 706.

Reynolds, S.P., 1988, in 'Galactic and extragalactic radioastronomy', Eds. G.L. Verschuur, K.I. Kellerman, Springer-Verlag.

Scheffler, H., Elsässer, H., 1987, 'Physics of the Galaxy and the interstellar medium', Springer-Verlag.

Tenorio-Tagle, G., 1982, in Regions of recent star formation, eds. R. Roger, P. Dewdnay, D. Reidel.

Tenorio-Tagle, G., Bodenheimer, P., 1988, ARA&A, 26, 145.

Terranegra, L., Chavarría, C., Díaz, S., González-Patino, D., 1994, A&AS, 104, 557.

Torres-Dodgen, A.V., Tapia, M., Carroll, M., 1991, MNRAS, 249, 1.

Weaver, R., McCray, R., Castor, J., Shapiro, P., Moore, R., 1977, ApJ, 218, 377.

Wendker, H.J., Higgs, L.A., Landecker, T.L., 1991, A&A, 241, 551.

Yorke, H.W., Tenorio-Tagle, G., Bodenheimer, P., Różyczka, M., 1989, A&A, 216, 207.