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Kinematics as a tracer of star formation triggered by massive stars

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Abstract. Gas dynamical consequences of the energetic output of massive stars have been considered as a possible feedback mechanism on star formation, with new generation of stars being formed from the masses of interstellar gas compressed and set in motion by the mechanical energy deposited by massive stars in their surroundings. A byproduct of this should be peculiarities in the motions of the resulting stars, which may be measurable with the accuracy available with present data. The detection of the kinematical signature associated to triggered star formation may then be used to constrain models. This paper briefly discusses ways in which massive stars can be responsible for the formation of new generations of stars, as well as some examples in which kinematics may provide the main support for a triggered star formation scenario. Some future perspectives made possible by planned space astrometry missions are also presented.

Keywords: kinematics, OB associations, feedback, massive stars.

1. Introduction

The interaction between the energetic output of massive stars and the interstellar medium is a major factor governing the physical conditions and large-scale structure of the gaseous component of galaxies, and as such it plays a major role in setting the initial conditions for star formation. We may divide the action of massive stars on their surrounding medium into two broad classes:

- Heating, dissociation, ionization of the interstellar medium, caused by the abundant ultraviolet radiation of massive early-type stars. The most visible manifestations are HII and photodissociation regions, reflecting changes in the physical and chemical conditions of the interstellar medium.

- Generation of large overpressures in localized regions of the galactic disk, caused by the mechanical energy deposited by stellar winds and supernova explosions, as well as by the large temperature increase when cold atomic or molecular gas is exposed to ultraviolet radiation. Associated structures are supernova remnants, wind blown bubbles, "worms" and "chimneys" observed in the large scale distribution of the galactic HI and, as an extreme example, the starbursts found at the centers of many galaxies. Such structures reveal changes in the dynamical conditions and large scale morphology of the interstellar medium induced by large increases in the gas pressure, caused in different ways by massive stars.

The second class of processes can impart large scale supersonic motions in the gas, and high compressions leading to further star formation. An interesting byproduct of star formation in such violent conditions is that the anomalous motions that lie at its origin may be observable as a relict in the second-generation stars. Stellar kinematics may thus be a tool for probing triggered star formation in a variety of scenarios, some of which will be discussed here.

Star formation triggered by supersonic motions of interstellar gas may take place and be easier to recognize at a *local* scale, namely in the proximities of the massive stars, clusters or associations that produce them. Some nearby possible examples will be presented in Section 3. Moreover, given the primary role of massive stars in driving the circulation of gas between the galactic disk and the halo, and the high velocity with which the return to the disk of gas expelled into the halo may take place, it seems appropriate to consider also star formation possibly resulting from this process as a form of feedback at a *large*, more indirect scale.

2. Large scale: star formation and the galactic fountain

It has been long recognized that the collective action of many massive stars and supernova explosions in OB associations should play a fundamental role in driving the circulation of gas between the galactic disk and the halo (Ikeuchi 1988; Mac Low 1999). "Tunnels" or "chimneys" where hot gas may be flowing away from the proximity of the galactic plane have been identified in HI observations of the Milky Way (Heiles 1992, Avillez 1998). Such structures are even more obvious in other galaxies, especially nearby edge-on ones having vigorous star formation in their disks (see e.g. Alton et al. 1998, Wills et al. 1999, García-Burillo et al. 2000 for recent examples) or central starbursts (Lehnert & Heckman 1995). Hot ionized gas expelled into the halo may cool down and recombine, probably being at the origin of at least some of the high velocity clouds (HVCs) observed in HI surveys at high latitudes (Wakker & van Woerden 1997). Such cycle of gas expulsion from the disk into the halo and further return to the disk in the form of HVCs is known as the galactic fountain.

2.1. Star formation in clouds colliding with the galactic disk

An obvious way in which the galactic fountain may trigger star formation is by collisions of HVCs with the galactic HI layer when they return to the proximities of the galactic plane. Such collisions were modelled by Tenorio-Tagle and collaborators (Tenorio-Tagle 1987 and references therein) and Comerón & Torra 1992, 1994, and invoked by several groups to explain structures such as the Orion-Monoceros complex (Franco et al. 1988), the Gould Belt system (Comerón & Torra 1994; see review by Pöppel in this volume) and some star forming complexes in the solar neighbourhood (Lépine & Duvert 1994). A similar origin has been proposed for the dispersed young stellar component observed around nearby star forming regions (Neuhäuser et al. 1997; see also the paper by Wichmann in this volume). Clump-clump collisions in HVCs, or instabilities induced in them by outflows of hot gas from the galactic disk, are also conceivable ways in which the galactic fountain may be responsible for triggered star formation away from the galactic disk.

If stars are indeed formed when HVCs collide with the galactic disk with velocities exceeding 100 km s^{-1}, the component of their initial velocities perpendicular to the galactic plane may reach several tens of km s^{-1}, the precise value depending on many factors such as the pre-shock velocity and pitch angle of the HVC, the density contrast between the HVC and the galactic HI layer, or the structure of both. They may thus resemble runaway OB stars, defined by their large space velocity despite of their youth. Formation mechanisms that have been proposed for normal OB runaway stars (ejection from a binary system after the supernova explosion of the companion, or from a dense stellar cluster after a close encounter with another member; Gies & Bolton 1986) are unrelated to the feedback mechanisms discussed here. However, they predict that, having formed in extreme Population I objects and therefore very near the galactic plane, they should be all moving away from the galactic disk, as their lifetimes are too short for their motion to be halted and reversed by the galactic gravitational potential (Gies 1987). This may not apply to "runaway" stars formed by HVC collisions with the galactic plane, however, if they form sufficiently high over the galactic plane and the resulting vertical velocity is low enough. For instance, a star formed 300 pc above the galactic plane with a velocity of 30 km s^{-1} would spend 10 Myr moving toward the plane with high velocity, rather than away from it as a normal runaway OB star would do. This number is a large fraction of the lifetime of an OB star. Recent *Hipparcos*-based investigations of OB and Wolf-Rayet stars (Lindblad et al. 1997, Moffat et al. 1998) do not find clear evidence for any short-lived massive stars far from the galactic plane and moving towards it, but further exploration of this intriguing possibility may reveal serious candidates to have been formed in HVC collisions.

2.2. Star formation far from the galactic disk

The existence of young stars at distances from the disk of the Milky Way too large to allow for their origin in the galactic plane has been suspected for some decades now. Although many candidates have been ruled out on the basis of careful spectral analyses, a few remain which are indistinguishable from normal early-type Population I stars (Little et al. 1995). If really formed in the halo, the origin of these stars is probably closely linked to the galactic fountain. The main evidence for star formation in these conditions comes in these cases from the very existence of these stars, rather than from their kinematics. Nevertheless, the latter has been used by Hambly et al. (1996) in an attempt to identify other apparently young stars around one of the candidate halo Population I stars, PHL 346, as a way to independently confirm its youth.

Recent independent evidence for ongoing star formation in a galactic halo testifies to the ability of a galactic fountain, or a related outflow phenomenon, of triggering star formation away from galactic disks. Comerón et al. 2000 have reported statistical evidence for an excess of blue objects, probably main sequence early B stars, in the direction of the halo of NGC 253 (Fig. 1). Some of them may be runaway stars of NGC 253, but a group lying at projected distances greater than 10 kpc from the disk may be the result of the interaction between

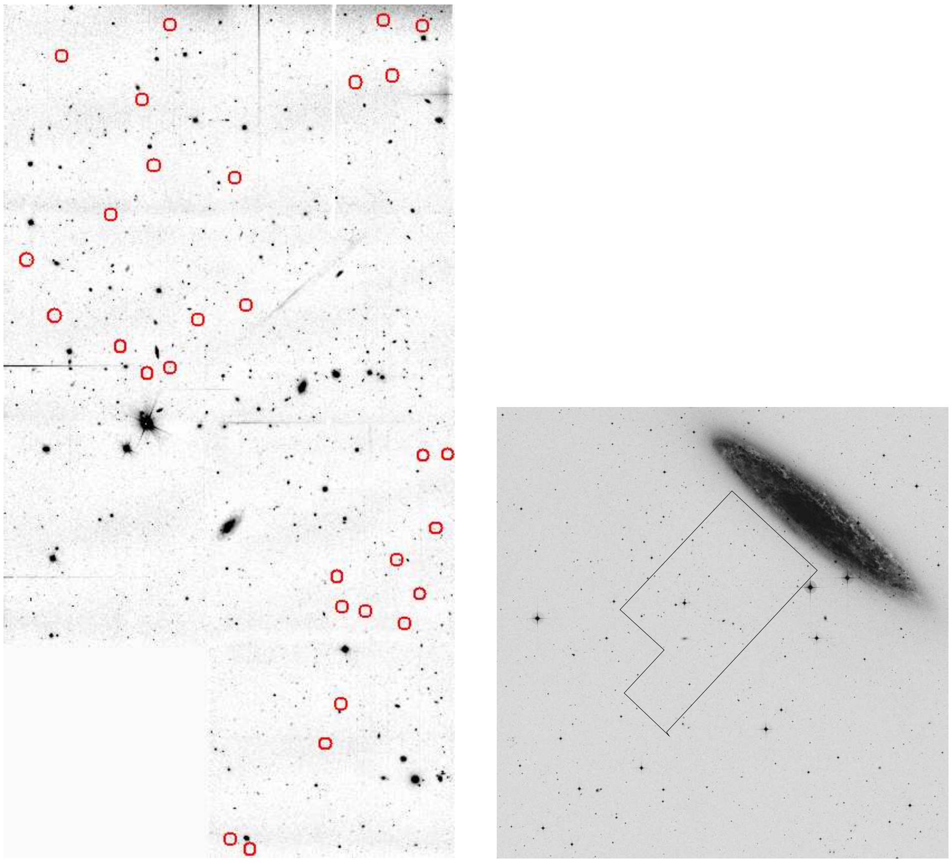

Figure 1. Bluest objects, possibly early main sequence B-type stars, detected in the direction of the halo of NGC 253. These stars may be the NGC 253 counterparts of early-type Population I stars suspected to exist in the halo of the Milky Way, and that may be formed by the action of the galactic fountain. This may thus be an exotic example of feedback mechanism on star formation driven by the energetic output of massive stars in the disk of the galaxy. In the case of NGC 253, the central starburst, absent in the center of the Milky Way, is likely to play an important if not dominant role in the galactic fountain. The image at left is a deep V band mosaic obtained with the ESO 3.5 m New Technology Telescope, while the image at right is a wide field ($40' \times 40'$ around NGC 253 from the Digitized Sky Survey outlining the countours of the deep field at left. From Comerón et al. (2000).

the superwind produced in the nuclear starburst of NGC 253 and denser gas in the halo. The example of NGC 253 is of course somewhat extreme in that the outflow involved is of a different nature from the galactic fountain expected in the Milky Way, and does not prove that the apparently distant Population I high latitude stars of our Galaxy are indeed young stars. Nevertheless, it does support the view that the combination of outflows and dense gas in galactic halos can lead to the formation of massive stars in such unusual environments.

3. Local scale: star formation in expanding structures

Large expanding shell-like structures in the interstellar gas associated to massive star formation sites are well known in ours and other galaxies (see e.g. Tenorio-Tagle and Bodenheimer (1988), Elmegreen (1998) for reviews, and the paper by Kawamura et al. in this volume for a nice example). The possibility of star formation in the compressed gas that forms these expanding shells by gravitational instabilities has been studied by McCray & Kafatos (1987) and Elmegreen (1994), among others. The Magellanic Clouds, due to their proximity, have been a favourite subject of many studies suggesting triggered star formation in shells (Domgoergen et al. 1995, Olsen et al. 1997, Efremov & Elmegreen 1998). More nearby examples have been proposed as well: evidence for triggered star formation in the nearest OB association, Scorpius-Centaurus, is presented by Preibisch and Zinnecker in this same volume. The Gould Belt as a possible example of triggered star formation will be discussed in the next section.

Hipparcos data allow detailed kinematical studies of nearby OB associations (de Zeeuw et al. 1999). Comerón et al. 1998 have used those data to search for kinematical traces of triggered star formation. The clearest example found by them is an expanding pattern of motions shared by OB stars scattered over an area of some 150 sq. degrees of the sky around Cygnus OB2, most of which belong to other OB associations (Fig. 2). The unusual richness of Cygnus OB2 in very early-type stars and the spatial coincidence of the expanding system of stars with the outline of the X-ray Cygnus Superbubble (Cash et al. 1980), all suggest a scenario in which the compression in an expanding shell around Cygnus OB2 would have give risen to the massive stars nowadays forming the neighbouring associations of Cygnus OB1, OB3, OB7, and OB9. Comerón et al. (1998) used a simple model of gravitational instability in an expanding shell to link its expansion velocity at the time of the onset of the instability with the mechanical output of the stars powering it, assuming that this expansion velocity has been preserved in the motions of the stars observed at the present. In this way, they were able to compare these energetic requirements with a rough estimate based on the present stellar contents of Cygnus OB2, finding an agreement to within one order of magnitude that is satisfactory in view of the many simplifying assumptions needed in the development of the model. We note however that a large variety of instabilities, not just gravitational, can affect expanding shells (Elmegreen 1998). All such instabilities tend to produce regions of high density where self-gravity may ultimately lead to collapse and star formation, even if it was not the initial factor determining the appearance of these high density regions. Thus, it may not be ruled out that other instabilities appeared before overall gravitational instability, and that the agreement

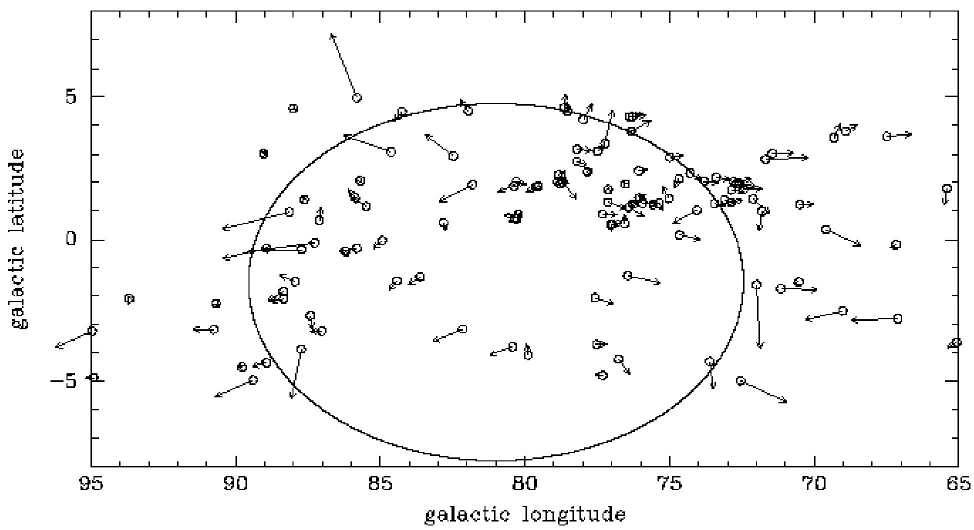

Figure 2. OB stars with proper motions measured by *Hipparcos* in Cygnus. The arrows mark the velocities in the plane of the sky, and are directed away from a point roughly coincident with the Cygnus OB2 association. The ellipse approximately outlines the contour of the Cygnus Superbubble, also centered in Cygnus OB2.

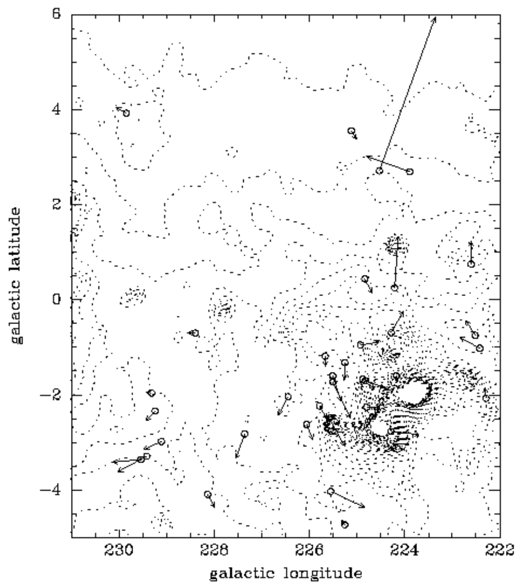

Figure 3. *Hipparcos* proper motions in Canis Major OB1 also show an expanding pattern. The fast star at the upper right is a newly identified runaway, perhaps the former companion of the supernova that triggered star formation in the region. The contours outline the 100 μm emission measured by IRAS. The peak on the lower right is the Canis Major R1 association.

found between the above mentioned energetic requirements and the estimated energetic output of Cygnus OB2 is a mere coincidence. In any case, regardless of the ultimate mechanism triggering star formation around Cygnus OB2, the kinematical evidence for triggered star formation in Cygnus seems to be clearly established by *Hipparcos* data.

Hipparcos data also show an expanding pattern suggestive of triggered star formation in the area of the Canis Major OB1 association (Fig. 3). Star formation triggered by a supernova in Canis Major R1, the only active star forming area remaining in the region, had been already suggested by Herbst and Assousa (1977), but the new *Hipparcos*-based results of Comerón et al. (1998) present a modified picture in which the whole OB association, and not only Canis Major R1, would have been formed in an explosive event. A difference from the Cygnus region in that a central engine does not exist at present in Canis Major, and the expansion velocities involved are also smaller (~ 15 km s^{-1} in Canis Major, as compared to ~ 25 km s^{-1} in Cygnus). Comerón et al. (1998) suggest that a single supernova, triggering instabilities and an expanding motion in a nearby massive molecular cloud, may have caused the formation of Canis Major OB1. In support of this scenario, that work notes the existence of a nearby runaway star whose motion can be traced back to the approximate center of expansion. The runaway was in that position about 1 Myr ago, consistent with the estimated age of the stars of the association. The runaway may thus be the former companion of the massive star that triggered the formation of Canis Major OB1.

4. Large or local scale? The Gould Belt

The Gould Belt is often quoted as a possible example of triggered star formation (see reviews by Pöppel (1997) and in this volume). A reason for this is the overall expansion displayed by its stellar and gaseous components, (see Torra et al. (2000) for recent work on the kinematics of the Gould Belt). The Gould Belt might thus be a local version of the associations in Cygnus described before: the present associations of the Gould Belt (Orion OB1, Scorpius-Centaurus, Perseus OB2) would be the counterpart of the associations around Cygnus OB2, while the old Cassiopeia-Taurus association (Blaauw 1991) would be a downscaled version of Cygnus OB2 itself (see Elmegreen 1992 for a description including other components of the Gould Belt, and Olano (1982) for a kinematical model; further support for an explosive origin of the Gould Belt is given by Pöppel & Maronetti 2000). The Gould Belt may thus be the nearest example of triggered star formation with a distinctive kinematical signature, of the type that we called "local" at the beginning. Nevertheless, such an origin for the Gould Belt does not seem to explain some intriguing features, such as the tilted distribution of its components (see Guillout's paper in this volume) with respect to the galactic plane. Moreover, it is unlikely in view of the present contents of the Cassiopeia-Taurus association that its most massive stars, already exploded as supernovae, may have been numerous enough to account for the large energy input needed by these models.

These unexplained features of the Gould Belt have prompted a search for alternative models eventually invoking a scenario of the *large scale* category, according to the definitions given at the beginning. Weaver (1974) was the first

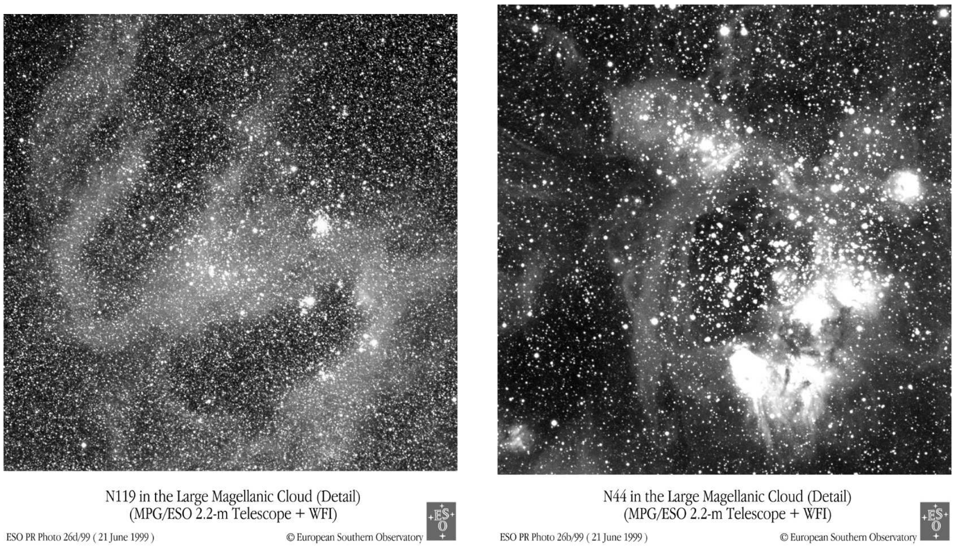

Figure 4. Two giant HII regions in the Large Magellanic Cloud, N119 (left) and N44 (right), imaged in Hα. The spiral shape of N119 has been tentatively interpreted as a result of the collision of two large HI clouds (Ambrocio-Cruz et al. 2000). The bubble that dominates the appearance of N44 is blown by the bright stars near its center, and contains numerous star forming regions along its rim. Images taken by the author using the Wide Field Imager at the ESO-MPI 2.2m telescope, courtesy of ESO.

to propose an origin of the Gould Belt linked to the infall of high velocity gas from the halo. This scenario was found to be plausible by Comerón and Torra (1992) based of two-dimensional gas dynamical simulations. Such a model does not attempt at explaining the kinematics associated to the Belt, as the capabilities of the numerical simulations are limited in this respect. However, as shown by Comerón (1999), the kinematical features of the Gould Belt, including the vertical motions of its stars, may be explained by the dispersion in space of an unbound tilted disk with an initial solid-body rotation pattern. Whether or not such an initial pattern of motions can be provided by a HVC impact on the galactic disk remains to be investigated, but in any case it is very likely that the observed stellar kinematics will play an important role in validating any proposed models for the origin of the Gould Belt.

5. Future prospects

Space astrometry missions planned for the near future, such as GAIA or FAME, will yield a hundredfold or more increase in parallax and proper motion accuracies over *Hipparcos*, while expanding the number of objects observed by approximately the same factor. This will open up the possibility of studying the fine spatial and kinematical structure of all OB associations of the galactic disk that are not too obscured to be observed at the visible wavelengths at which these missions will operate. We may thus expect a much more detailed view on the internal processes of star formation in clusters and associations, including kinematical clues to the way that gas motions have influenced them. The resolution that will be attained for the tangential velocities in associations within a few kiloparsecs from the Sun will be above the turbulent and thermal velocities in molecular clouds, as compared with present day resolutions of the order of the thermal velocities in the warm, diffuse interstellar gas. This will allow the probing of a much broader range of mechanisms of triggered star formation, leaving kinematical imprints at those velocity levels.

The precise parallaxes for stars at the distances typical of remote halo objects will allow to directly test the reality of the existence of young objects at large distances from the galactic disk. If confirmed, this will strongly support the ability of galactic outflows to trigger star formation in normal haloes such as the one of the Milky Way, and not only in higher energy environments such as the outflows associated to AGNs and starbursts. In this way, these observations will extend the range in distances and environments at which feedback mechanisms having their origin in disk massive stars can operate.

The expected accuracies of future space astrometry missions translate into tangential velocities at the few km s^{-1} level at the distance of the Magellanic Clouds. As noted at the beginning of Section 3, many cases of likely triggered star formation along the rims of large expanding rings have been studied in detail in the Magellanic Clouds. The resulting kinematical signature may well be visible in measurements carried out down to such levels of accuracy, putting strong constraints on the mechanisms and input parameters of models. The variety of morphologies displayed by giant HII regions in the Magellanic Clouds (Fig. 4 gives two representative examples) strongly suggests that gas dynamics in these regions plays an important role in driving star formation, and measuring the velocities of the resulting stars may well be the only way in which hypotheses on the origin of some of these regions can be effectively tested.

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