multi-fibre surveys. Although the ESS is not in proportion with these large-area surveys to come in terms of survey volume, budget, and manpower, it provides an anticipated understanding of the properties of the galaxy distribution at large distances.

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Massive Stars Running Through Space

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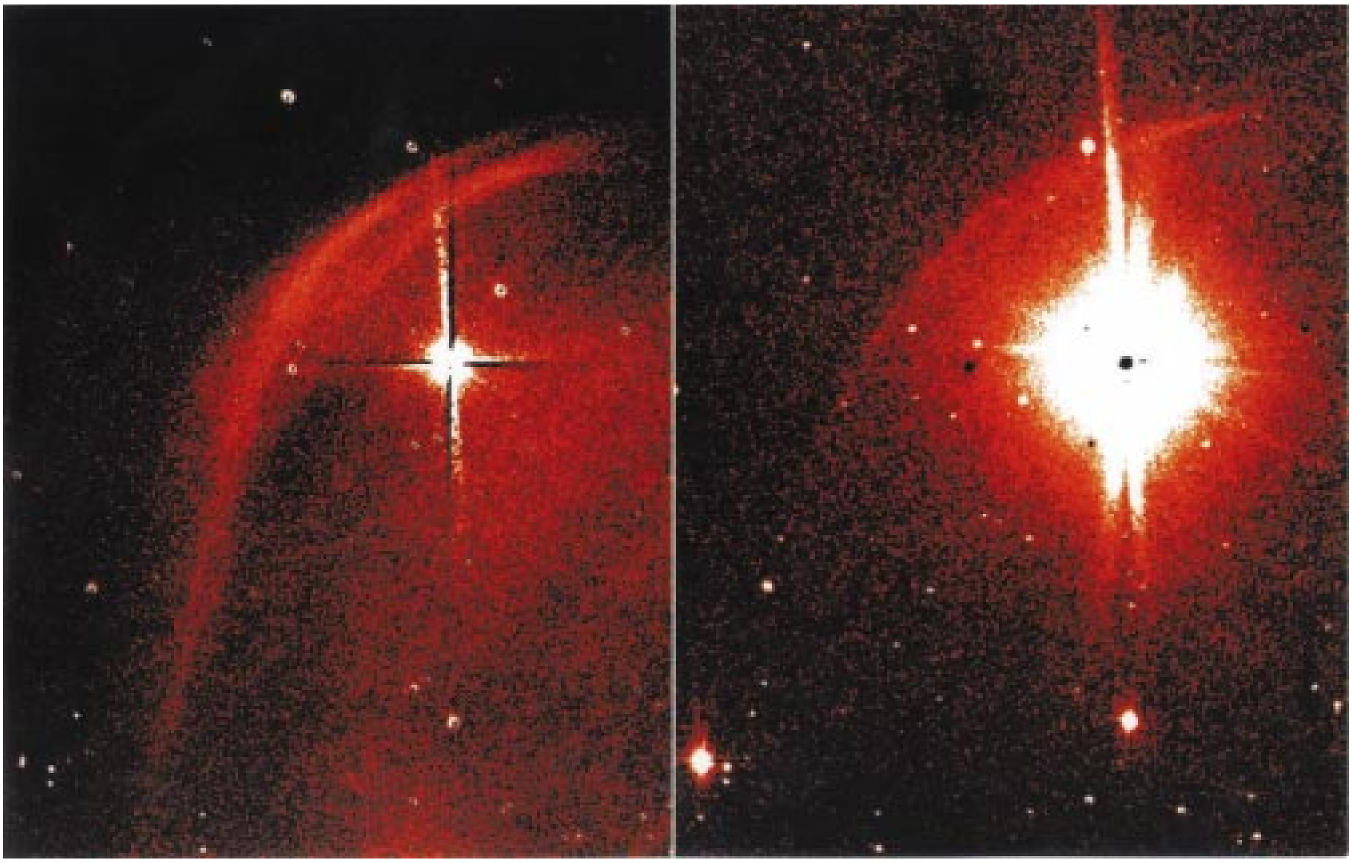
1. Introduction

OB runaways are massive (OB) stars that travel through interstellar space with anomalously high velocities. The space velocity of these stars can be as high as 100 km/s, which is about ten times the average velocity of "normal" OB stars in the Milky Way. Many of them can be traced back to a nearby OB association where they seem to have originated from. But how did these massive stars obtain such a high velocity? Recent observations carried out at the European Southern Observatory have provided compelling evidence that, at least in one case, the supernova explosion of a massive binary companion is responsible for the large space velocity gained by the remaining OB star. The observational evidence is based on the discovery of a wind bow shock around the high-mass X-ray binary Vela X-1, an X-ray pulsar with a B-supergiant companion. Here we report on new high-resolution coronographic observations of the bow shock obtained with ESO's *New Technology Telescope.* Furthermore, we present the first results of hydrodynamical calculations simulating the interaction between the interstellar medium and the stellar wind of a B supergiant moving with a supersonic velocity.

According to Blaauw (1961), a "bona-fide" runaway star fulfils two criteria: (i) it has an observed high (i.e. > 30 km/s) space velocity and (ii) a "parent" OB association has been identified. It turns out that a significant fraction of the OB stars are runaways; their frequency steeply decreases as a function of spectral type: from about 20% among the O-types to 2.5% among B0-B0.5, and still lower among B1–B5 (Blaauw, 1993). Almost all runaways appear to be single;



Narrow-band Hα (left) and [O III] (right) images of the wind bow shock around the runaway binary HD77581 (Vela X-1) obtained with the NTT in January 1996. North-west is up and north-east to the left. The distance between the bow shock's apex and the supergiant is 0.9 arcminutes, which corresponds to 0.5 parsec at the distance of 1.8 kpc. To suppress the bright B supergiant's light (V = 6.9 mag) we used a coronographic plate. Additionally, a scaled R-band frame was subtracted to further reduce the remaining stellar light. The Hα image clearly shows the 3-dimensional cone structure of the bow shock and the filamentary structure in front. Obviously, the system is moving to the north. Comparison of the Hα and [O III] images shows that the [O III] emission originates from a region in front of the (denser) part of the bow shock seen in Hα.

only in a very few cases a runaway is confirmed to be part of a binary or multiple system (Gies & Bolton, 1986). The average distance with respect to the galactic plane is much larger for confirmed runaways than for cluster and association members (Gies, 1987). Although based on small-number statistics, OB-runaways also tend to have high (projected) rotational velocities and relatively high surface helium abundances (Blaauw, 1993).

The majority of massive stars are members of an OB association or a cluster; e.g., for the O stars about 70% belong to a cluster or association (Gies, 1987); given the large fraction of O-runaways, it might well be that all O-type stars were born in associations and that the whole field population consists of runaway stars. The study of runaway stars is, therefore, intimately related to the problem of massive-star formation and evolution.

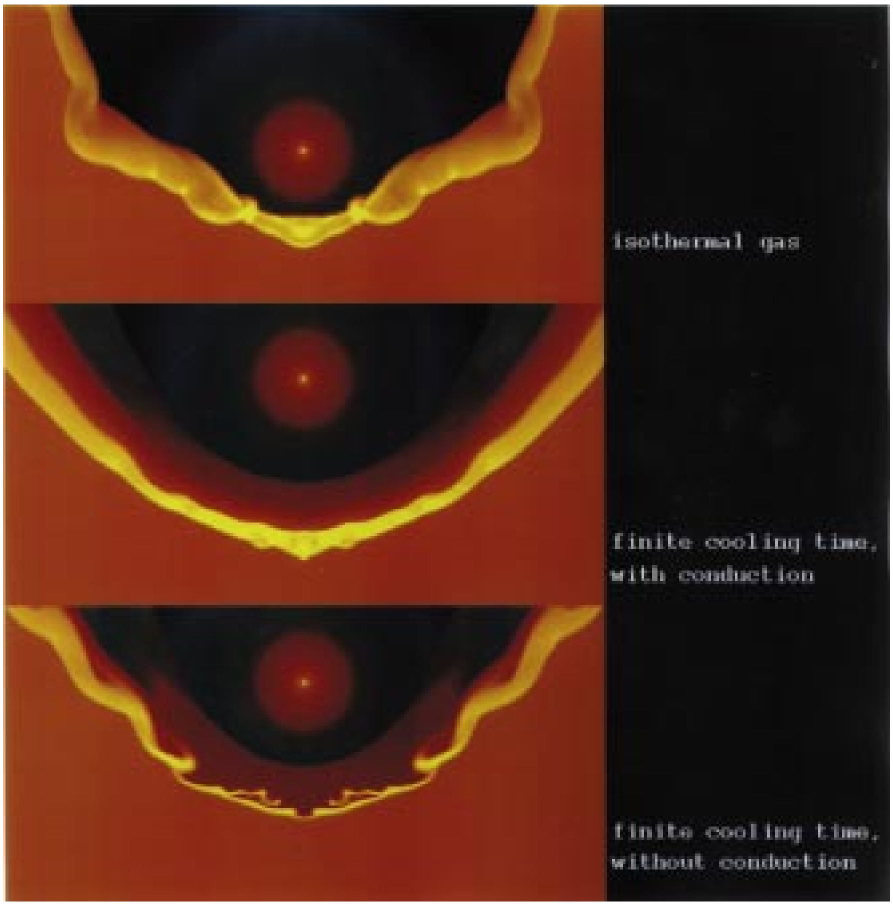
2. How are OB-Runaways Formed?

The two most popular scenarios for the formation of runaway stars are the binary supernova model (Blaauw, 1961) and the cluster ejection mechanism (Poveda et al., 1967). Blaauw suggested that when an OB star is bound to another OB star in a binary system, the supernova explosion of one of the stars (i.e. the initially most massive one) causes the disruption of the binary system since more than half of the total mass of the system would be lost after the supernova explosion of the primary. As a consequence, the remaining massive star escapes preserving its (relatively high) orbital velocity. The modern version of this scenario includes a phase of mass transfer inverting the original mass ratio, so that the resulting runaway star has a large probability to remain bound to the compact remnant (a neutron star or a black hole) produced by the supernova. The mass transfer from the evolved star to the future runaway star could increase its atmospheric helium abundance. Furthermore, the angular momentum associated with the accreted material would result in a higher rotation rate of the future runaway. The binary supernova model predicts that many OB runaways should have a compact companion. Searches for compact stars around OB runaways have, however, up to now not been successful (e.g. Philp et al., 1996).

An alternative explanation for the existence of OB-runaway stars is the cluster ejection model: the dynamical interaction in a compact cluster of stars results in the ejection of one or more of the members. From their extensive radial velocity survey of bright OB-runaway stars, Gies & Bolton (1986) concluded that the cluster ejection model has to be favoured. Apart from the lack of observational evidence for the presence of compact companions around OB runaways, the existence of 2 runaway double-lined spectroscopic binaries cannot be explained with the supernova model. Also the kinematical age of OB-runaway stars (i.e. the time needed to reach its present position with respect to the "parent" OB association) is often close to the age of the OB association itself, which would be in support of the cluster ejection model. In the following we will argue that at least in one case the supernova scenario applies.

3. A Wind Bow Shock Around Vela X-1

Kinematic studies of OB stars are hampered by the large distances at which these stars are usually found, making it very difficult to measure proper motions accurately (although this situation has significantly improved after the release of the *Hipparcos* data). But it turns out that many OB stars with high



These panels show the results of numerical simulations of the bow shock produced by a runaway star with the wind parameters derived for HD 77581 (Vela X-1), moving at 90 km/s in a medium with a density of one hydrogen atom cm^{-3}. Shown is the gas density. Different hypotheses about the physical behaviour of the gas are made in each case: in the middle panel, the gas is allowed to cool down by radiation and to transport energy by conduction. In the top panel, it is assumed to be isothermal, at a temperature of 8500 K. In the bottom panel, thermal conduction has been suppressed. Each panel covers an area of 4.4 × 2.2 parsec. The simulations indicate that a filamentary structure of the bow shock is expected.

space velocity create an unmistakable sign in the surrounding space. When an OB star moves supersonically through the interstellar medium (ISM), the interaction of its stellar wind with the ISM gives rise to a bow shock. Van Buren & McCray (1988) inspected the IRAS all-sky survey at the location of several OB-runaway stars and found extended arc-like structures associated with many of them. The infrared emission results from interstellar dust swept up by the bow shock and heated by the radiation field of the OB-runaway star. In a subsequent study (Van Buren et al., 1995), wind bow shocks were detected around one-third of a sample of 188 candidate OB-runaway stars. Thus, the detection of a wind bow shock can be considered as an observational confirmation of the runaway status of an OB star.

Recently, such a wind bow shock was discovered around the high-mass X-ray binary (HMXB) HD 77581 (Vela X-1), indicating a high space velocity of the system (Kaper et al., 1997). HD 77581 is the B-supergiant companion of the X-ray pulsar Vela X-1. The supergiant's strong stellar wind is partly intercepted by the orbiting neutron star resulting in the observed (pulsed) X-ray flux. Obviously, this binary system experienced a supernova explosion which resulted in the formation of Vela X-1. Due to a phase of mass transfer, the supernova remnant (in this case a neutron star) could remain bound to its massive OB-star companion when the system received a large kick velocity. The short ($\sim 10^4$ years) HMXB phase starts when the OB-star becomes a supergiant. The observed wind bow shock not only indicates the runaway nature of Vela X-1, it also shows the direction of motion of the system. Most likely, Vela X-1 originates from the OB association Vel OB1; then, the kinematical age of the system is 2 to 3 million years, which would be consistent with the expected time interval between the supernova explosion of the primary and the subsequent evolution of the secondary into a supergiant (Van Rensbergen et al., 1996). The new *Hipparcos* measurements confirm this result: the space velocity of the system is about 50 km/s with respect to the OB association (which is less than the 90 km/s quoted in Kaper et al., 1997).

In Figure 1 we present new high-resolution images of the wind bow shock around Vela X-1 obtained with the *New Technology Telescope* at La Silla. We used the narrow-band Hα (excluding the [N II] line) and [O III] filters, plus a coronographic plate to suppress the large flux produced by the V = 6.9 mag (!) B supergiant. Furthermore, a properly scaled R-band image was used to remove (as far as possible) the remaining parts of the PSF and internal reflections (this does not work very well for the [O III] image due to the colour difference). The filamentary structure of the wind bow shock is present for both filters. In three dimensions the bow shock has a parabolic shape. Hα photons produced by the far side of the bow shock appear in this image as a sharp contrast between the front and far side of the bow shock. A comparison of the Hα and [O III] images shows that the [O III] emission originates from a region in front of the (denser) part of the bow shock seen in Hα (use the "remnants" of the surrounding stars as a reference). To determine the spatial separation between the regions producing Hα and [O III] emission, projection effects should be taken into account.

4. Hydrodynamical Simulations

In order to interpret these observations, we performed hydrodynamical simulations of the interaction process between the stellar wind of the runaway system and the interstellar medium. The observed bow shock is only the outermost layer of a more complex structure, whose characteristics are determined by the efficiency of the different physical processes operating in the interstellar gas. Proceeding away from the star, one finds in the first place the region of freely flowing wind. This region is bounded by a strong shock, where most of the kinetic energy of the wind is transformed into thermal energy. The hot, low-density shocked gas has a rather slow cooling rate and, while flowing downstream, it provides a cushion supporting the bow shock against the ram pressure of the ambient gas. The high temperature of the shocked stellar wind, in contact with the warm, dense gas from the ambient medium accumulated in the bow shock, produces an intense flow of energy from the hot to the warm gas by thermal conduction. The effects of this energy flow are to keep the temperature of the shocked wind at a value of a few million degrees, and to evaporate dense gas from the bow shock into the hot interior. This produces an interface of intermediate density and temperature between the shocked wind and the bow shock.

In Figure 2 a simulation is shown of the bow shock using the parameters for Vela X-1 derived by Kaper et al. (1997), arbitrarily turning off some of the relevant physical processes in the gas in order to estimate their relative importance. The frame in the middle shows the structure outlined above, with both radiative cooling and thermal conduction at work in the hot gas. The top frame shows the same results, but now assuming that the shocked wind is able to instantaneously cool down to a temperature of 8,500 K, the same as the ambient gas. The shape of the bow shock is in this case much more irregular; this is due to the chaotic motions induced by Kelvin-Helmholtz instabilities when the gases coming from the ambient medium and from the stellar wind, having very different velocities along the bow shock, get in contact. Finally, the bottom frame is the same as the middle one, but now without allowing energy transport by thermal conduction. Also in this case, the bow shock becomes unstable, with ripples and filaments appearing all along its inner surface. The sharper jump in density from the shocked wind to the bow shock is also apparent in this case. These simulations are described in detail by Comerón & Kaper (1997, in preparation).

In conclusion, we see that the observation of a wind bow shock around Vela X-1 provides support for Blaauw's scenario for the production of runaway stars. The wind bow shock itself provides an interesting laboratory to study the hydrodynamical processes involved in the collision of stellar wind particles moving at 1% of the speed of light with the interstellar medium that "approaches" the star with a supersonic velocity.

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Oph 2320.8–1721, a Young Brown Dwarf in the ρ Ophiuchi Cluster: Views from the Ground and from Space

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A variety of observational techniques have provided over the last few years the first reliable identifications of brown dwarfs and extrasolar planets, detected either by direct observations or by the gravitational effects on the stars they orbit. The list of the best brown-dwarf candidates known so far includes members of multiple systems, cluster members, and free-floating objects, as well as moderately young and more evolved objects. Likewise, the list of probable extrasolar planets, although still short, already includes objects covering a fairly large range of masses, distances to the central star, and eccentricities, thus suggesting the existence of several different scenarios for their formation and orbital evolution. The combination of new observational data and theoretical developments is leading to a vigorous activity in this field (Rebolo, 1997).

The observation of brown dwarfs in their earliest evolutionary stages is an important ingredient in our understanding of the formation and the characteristics of substellar objects. These objects sample a particular region of the temperature-surface gravity diagram, already abandoned by the more evolved objects discovered so far. They are still bright and hot, emitting most of their luminosity in the near-infrared. Their presence in clusters allows the study of coeval samples with well-constrained ages, and the determination of the mass function down to substellar masses. One of the best-studied very young, nearby clusters is the one near ρ Ophiuchi, usually referred to as "the ρ Ophiuchi cluster". Its proximity to the Sun (160 pc) and its age (a few million years) places its brown dwarfs well within the reach of arrays operating in the near-infrared, where the abundant dust in which the cluster members are still embedded is much more transparent than at visible wavelengths. The dust also helps by providing a natural screen against background sources unrelated to the cluster, whose density per unit area is already reduced by the relatively large distance of the cluster to the galactic equator.

In practice, the identification of a brown dwarf in an embedded cluster is complicated by several factors. Such an identification has to be done based on the luminosity, which allows an estimate of the mass by means of theoretical models (Burrows et al., 1993, D'Antona & Mazzitelli, 1994) provided that the age of the object is known. Unfortunately, the luminosity is difficult to assess, as the foreground dust absorbs most of the energy emitted at short wavelengths, including the near-infrared where the intrinsic spectral energy distribution of the object peaks. Also, a part of the luminosity of the object can be reprocessed by a circumstellar disk or envelope, which is a common feature in very young objects. On the other hand, the rapid decrease of the luminosity of a very low mass object with time requires a precise knowledge of the age for a reliable mass estimate. However, this is not so demanding in the case of brown dwarfs, due to the temporary stability in the luminosity output by deuterium burning in the core, which can last for a time comparable to the duration of the embedded stage. These problems were considered by Comerón et al. (1993, 1996), who were able to derive mass functions down to $\sim 0.04\ M_\odot$ for both ρ Ophiuchi and NGC 2024 using mostly J, H and K band photometry. Nevertheless, the masses of individual objects in each of those aggregates was rather poorly constrained, due to the difficulty of reconstructing the intrinsic spectral energy distribution from the available JHK photometry alone.

The possible substellar character of one of the most promising brown-dwarf candidates identified in ρ Ophiuchi, Oph 2320.8–1721, was already pointed out by Rieke & Rieke (1990), who tentatively assigned to it a mass of $0.06\ M_\odot$. This estimate was further reduced by Comerón et al. (1993), based on the need of assuming a moderate circumstellar infrared excess to fit the available photometry. A major step in supporting the brown-dwarf nature of Oph 2320.8–1721 came from its spectrum in the 2 µm region presented by Williams et al. (1995), whose features clearly confirmed the low photospheric temperature