Stellar Winds in High-Mass X-Ray Binaries

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Abstract. High-mass X-ray binaries (HMXBs) provide important observational diagnostics for the study of massive stars, their stellar winds, and the nature of accreting compact X-ray sources. In wind-fed systems, the X-ray flux produced strongly depends on the local wind velocity, making the X-ray source a sensitive probe of the stellar-wind structure. A comparison of observed and predicted X-ray luminosities suggests that the wind speeds at the orbit of the X-ray source are lower than expected for the usual $\beta = 1$ velocity law. An explanation for this is that the X-ray source is embedded in an extended region of high ionization in which the radiative acceleration of the stellar wind is suppressed. This effect also gives rise to the formation of a strong shock at the trailing border of the ionization zone where the stagnant flow meets the undisturbed stellar wind. Preliminary results based on infrared observations obtained with the ISO satellite are presented.

On a much larger spatial scale, the impact of stellar winds in HMXBs can be observed as well. Scenarios for massive binary evolution predict that HMXBs receive a large kick velocity during the supernova explosion of the compact star's progenitor. One might, therefore, expect to observe wind bow shocks around these systems such as observed around many OB-runaway stars. Such a wind bow shock has recently been discovered around the system Vela X-1.

1. Probing the Disrupted Stellar Winds of HMXBs

In a high-mass X-ray binary (HMXB) a massive, OB-type star transfers mass onto a compact companion (a neutron star or a black hole). Accretion of this material results in the observed X-ray flux. In wind-fed systems, the dense stellar wind of the massive star is partly intercepted by the strong gravitational field of the compact companion and accretes. A more extreme case of mass transfer occurs when the massive star overflows its Roche lobe; this leads to a flow of matter through the inner Lagrangian point towards the compact star, and the formation of an accretion disk. The massive star is either an OB supergiant with a radiation-driven wind or a Be star which is characterized by strong Hα emission formed in a slowly outflowing, dense equatorial disk.

The accretion-induced X-ray luminosity gives a direct measure of the wind density and velocity at the orbit of the X-ray source:

$$L_{\rm X} \propto \dot{M} v_{\rm rel}^{-4},$$

Table 1. HMXBs with OB-supergiant companions. The orbital and pulse periods are taken from Van Paradijs (1995). Most of the systems contain an X-ray pulsar, identifying the compact object as a neutron star. The terminal wind speed, v_∞, and mass-loss rate, $\dot{M}$, are estimated on the basis of spectral type and luminosity of the supergiant (see text). For most systems the observed X-ray luminosity is strongly variable; we took the mean value of the observed minimum and maximum flux. The distance is in most cases rather uncertain. References are: (*a*) Crampton et al. (1985); (*b*) Van Kerkwijk et al. (1995); (*c*) Hutchings et al. (1983); (*d*) Kaper et al. (1995); (*e*) Kaper et al. (1993); (*f*) Van Kerkwijk et al. (1989); (*g*) Herrero et al. (1995).

System	Sp. Type	$P_{\rm orb}$ (days)	$P_{\rm pulse}$ (sec)	v_∞ (km s^{-1})	$\dot{M}$ ($M_\odot$ yr^{-1})	$\langle L_X \rangle_{\rm obs}$ (erg s^{-1})	D (kpc)
0114+650 [a]	B0.5 Ib	11.60	850	1400	4×10^{-7}	1.7×10^{35}	4
SMC X-1 [b]	B0.5 Ib	3.89	0.72	800	9×10^{-8}	2.6×10^{38}	58.9
LMC X-4 [b]	O7 III–V	1.41	13.5	2000	1×10^{-7}	2.2×10^{38}	51.3
LMC X-1 [c]	O7–9 III	4.22		2000	2×10^{-7}	9.6×10^{37}	51.3
Vela X-1 [b]	B0.5 Ib	8.96	283	1105	4×10^{-7}	4.6×10^{36}	1.8
Cen X-3 [b]	O6.5 II–III	2.09	4.82	2400	6×10^{-7}	2.6×10^{37}	7.9
GX301−2 [d]	B1.5 Ia+	41.50	681	400	2×10^{-5}	3.7×10^{37}	5
1538−52 [b]	B0 Iab	3.73	530	1500	9×10^{-7}	2.1×10^{36}	7
1700−37 [e]	O6.5 Iaf+	3.41		1820	6×10^{-6}	9.8×10^{35}	2.5
1907+097 [f]	B0.5 Ib	8.38	438	1100	4×10^{-7}	5.8×10^{36}	4
Cyg X-1 [g]	O9.7 Iab	5.60		2100	3×10^{-6}	1.3×10^{37}	2.5

where $\dot{M}$ is the wind mass-loss rate and $v_{\rm rel}$ the velocity of the stellar wind with respect to the compact object. Thus the X-ray source acts as a sensitive probe in the stellar wind. In Table 1 we list the best-studied HMXBs with OB-supergiant companions (on which we will concentrate in the following). The system parameters are collected from literature (for each system a reference is given) and serve as input to calculate the predicted X-ray luminosity resulting from wind accretion (Bondi & Hoyle 1944). For HD 77581 (Vela X-1) and HD 153919 (1700−37) the terminal wind velocity v_∞ is measured from the UV P-Cygni lines. For the other systems an estimate of v_∞ is based on the spectral type of the supergiant (Prinja et al. 1992). The mass-loss rate is derived from the luminosity (and effective temperature) of the OB supergiant, using the fitting formula of Lamers & Leitherer (1993). Note that the distances (and therefore the absolute luminosities) are generally rather uncertain.

Due to the lower metallicity (Z) of the Magellanic Clouds, and therefore the different line spectrum, the radiation-driven winds have lower terminal velocities and lower mass-loss rates compared to those of Galactic OB stars (Kudritzki et al. 1987). To take these effects into account, we subtracted 600 km s^{-1} (LMC) or 1000 km s^{-1} (SMC) from the v_∞ listed by Prinja et al.; the mass-loss rate is assumed to be reduced by a factor $\sqrt{Z/Z_\odot}$ compared to the mass-loss rate derived for solar abundances. In all cases, a $\beta = 1$ wind velocity law is adopted.

Inspired by White (1985), we constructed a diagram (Fig. 1) comparing the observed and predicted X-ray luminosity for the OB-supergiant systems in

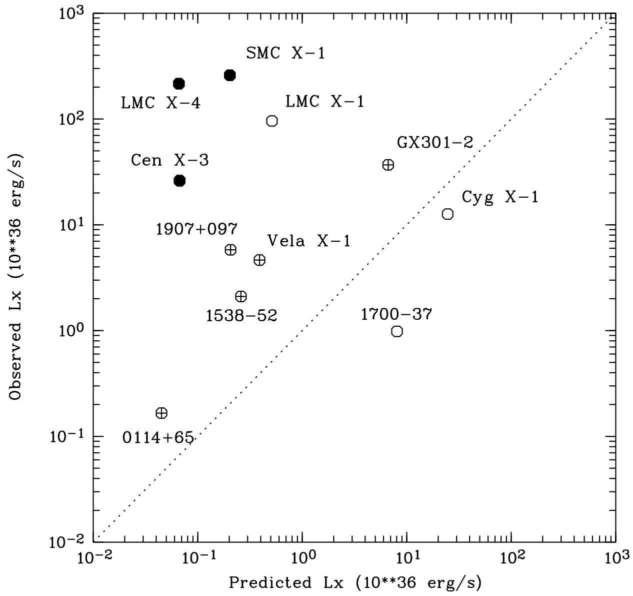

Figure 1. Observed versus predicted X-ray luminosity for the systems listed in Table 1. In the calculations it was assumed that the X-rays result from wind accretion only. The filled symbols indicate systems with a rapid X-ray pulsar ($P_{\rm p} < 20$s); these systems undergo Roche-lobe overflow and contain an accretion disk. The observed X-ray luminosities are therefore much higher than predicted. The crossed symbols represent wind-fed systems with a slow X-ray pulsar; the observed X-ray luminosity is about a factor 10 higher than predicted. The open symbols show systems for which no X-ray pulsations have been detected.

Table 1. These sources usually have a strongly variable (factor ~10–100) X-ray luminosity, which might be related to the instability of the accretion process and/or inhomogeneities in the stellar wind. We took the mean of the observed minimum and maximum X-ray flux to derive the observed X-ray luminosity. Several systems contain an (eclipsing) X-ray pulsar, so that the orbits and other fundamental stellar parameters (e.g., masses of the binary components, stellar radius) are accurately known (Nagase 1989; Van Kerkwijk et al. 1995).

Systems with a rapid X-ray pulsar (Cen X-3, LMC X-4, SMC X-1) appear to have a much higher X-ray luminosity than expected from wind accretion. These systems experience a phase of Roche-lobe overflow, resulting in a much higher accretion rate and spin-up of the X-ray pulsar; they do not provide a strong constraint on the stellar-wind structure.

The HMXBs containing a slow pulsar (crossed symbols) are thought to be 'pure' wind-fed systems; this seems to be supported by the fact that they are found close to the dotted line in Fig. 1. However, they have observed X-ray luminosities which are systematically about a factor 10 higher than predicted. The recent reclassification of Wray 977 (GX301−2) as a hypergiant (with much

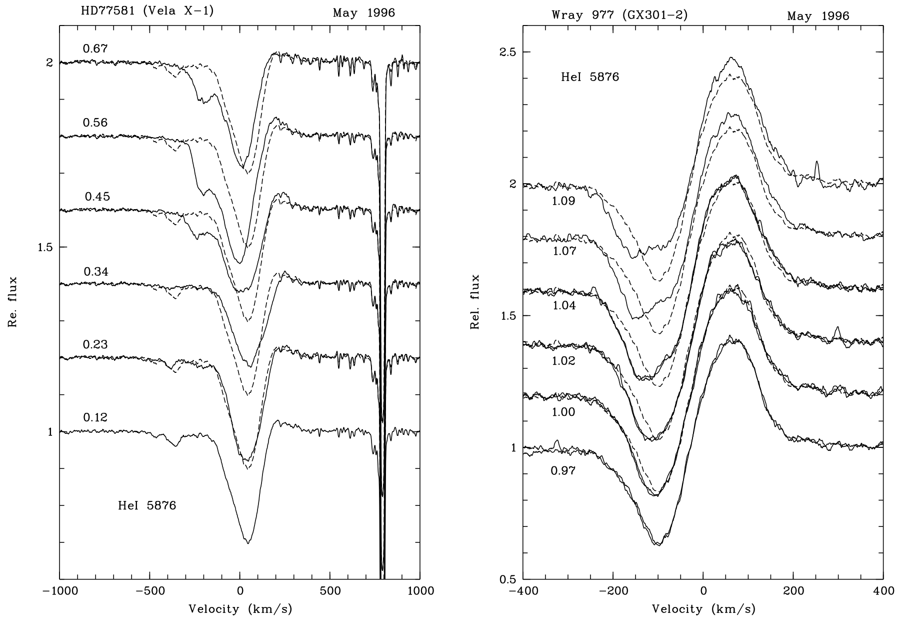

Figure 2. Time series of the He I λ5876Å line of HD 77581 (Vela X-1, left) and Wray 977 (GX301−2, right). The orbital phase is indicated: for the eclipsing system Vela X-1, phase 0 corresponds to X-ray eclipse, in the non-eclipsing, eccentric-orbit ($e = 0.47$) system Wray 977 phase 0 defines periastron passage. In the latter system the line of sight is crossed at phase 0.95. The dashed line represents the spectrum displayed at the bottom of each figure.

higher mass-loss rate and lower terminal velocity than a 'normal' B supergiant) puts it in line with the other wind-fed systems (Kaper et al. 1995). HMXBs for which no X-ray pulsations have been detected are shown as open symbols. These systems, especially LMC X-1 and Cyg X-1, are firm black-hole candidates. Although we took the differences in stellar-wind parameters into account, the Magellanic Cloud systems seem to have a systematically higher X-ray luminosity compared to Galactic systems. It might be that interstellar X-ray absorption has not been properly corrected for, or that the accretion mechanism is dependent on metallicity.

What could be the explanation for the $\sim 10\times$ higher X-ray luminosity observed for the wind-fed systems? This difference is most likely a consequence of the impact the X-ray flux has on the wind-acceleration mechanism. In Be/X-ray binaries, the Be-star wind seems to be rather unaffected by the relatively low X-ray flux, due to the usually wide and eccentric orbit of the compact star. In OB-supergiant systems, however, the strong X-ray flux significantly increases the degree of ionization in the surrounding wind regions, resulting in the formation of an extended Strömgren zone that trails the X-ray source in its orbit. This causes the observed modulation of UV P-Cygni profiles (e.g., of the resonance lines of Si IV and C IV) with orbital phase (Hatchett & McCray 1977; Kaper et al. 1993).

Inside the Strömgren zone the radiative acceleration of the wind is quenched, because the spectral lines formed in this highly ionized plasma cannot support the radiative acceleration of the flow; the lines are concentrated at X-ray wavelengths where the OB supergiant does not provide sufficient flux. Thus the velocity of the stellar wind is probably almost constant throughout the ionization zone, and about equal to the velocity the wind has reached before entering it. This could easily result in a reduction of the wind speed at the orbit of the X-ray source of a factor of two (compared to that for the usual $\beta = 1$ velocity law), which would be more than sufficient to explain the factor 10 difference in X-ray luminosity ($L_X \propto v_{rel}^{-4}$).

Another consequence of the suppression of the radiative acceleration inside the ionization zone is the formation of a strong shock at the zone's trailing border, where the unaffected wind meets the stagnant flow (see, e.g., Blondin et al. 1990). The presence of this 'photoionization wake' is observationally confirmed in Vela X-1 and 1700−37 (Kaper et al. 1994). Recent observations of Wray 977 (GX301−2) indicate that in this system, too, an extended region of high-density gas is trailing the X-ray source in its orbit (Fig. 2).

2. Infrared Observations of HMXBs

A powerful method to determine the velocity and density structure of OB-star winds is available for the infrared (IR) wavelength domain (cf. Lamers & Waters 1984). Free-free and free-bound emission is produced in the inner part of the stellar wind (where most of the acceleration takes place) and can be modelled in a rather straightforward way. The derived slope of the IR continuum constrains the velocity and density structure of the wind very well. Furthermore, this emission process is not very sensitive to the degree of ionization and the temperature structure of the wind.

The focus of our observing programme with the Infrared Space Observatory (ISO) project is to observe a sample of HMXBs (including the supergiant systems Vela X-1, 1700−37, GX301−2, and Cyg X-1 discussed here) at different orbital phases. For the eclipsing systems a comparison of the IR flux at superior and inferior conjunction should result in a direct measure of the mass-accretion flow towards the X-ray source. The photometric observations we obtained up to now (at 6.75, 11.5, and 25μm) result in (average) flux levels consistent with our predictions (see Kaper et al. 1997a). As an example we discuss the (preliminary) results on the eclipsing system HD 153919 (1700−37). ISO observations were obtained at four different orbital phases in one orbit of the system. The observed 6.8μm flux (670 mJy) is constant within 1%. This is not surprising, since at this wavelength the contribution from the stellar wind should be small. In Fig. 3 the measured 11.5μm flux is plotted against orbital phase; the flux reaches a maximum at phase $\phi = 0.46$ (X-ray source in front) and a minimum at $\phi = 0.71$. The predicted 11.5μm flux of HD 153919 is 180 mJy (the wind contribution should be about 25%), which is in between the observed values at $\phi = 0.71$ and 0.96. The source is also detected at 25μm (flux levels around 100 mJy), but

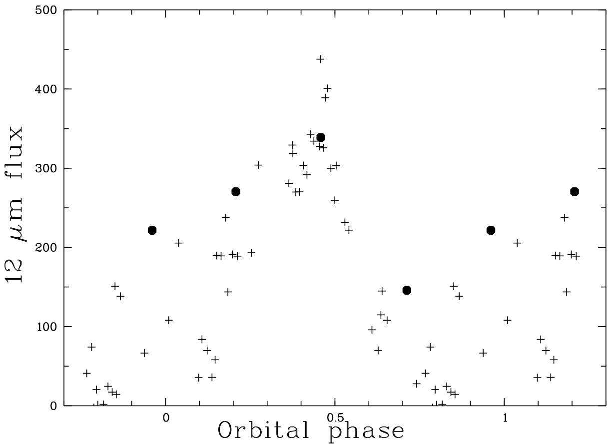

Figure 3. The flux of HD 153919 (1700−37) at 11.5μm (in mJy) as a function of orbital phase (filled circles). The measurement error is about 15 mJy. The 11.5μm flux reaches a maximum at phase 0.5 (when the X-ray source is in front of the supergiant) and is minimal at phase 0.75. The crosses indicate the integrated flux (scaled) of Raman-scattered emission lines observed for this source in the ultraviolet wavelength domain. Note that both quantities vary in concert.

the present calibration of ISOPHOT is too uncertain to determine an eventual dependence on orbital phase.

Before interpreting the 11.5μm flux variation of HD 153919 we note that the X-ray source is strongly variable ('flaring') on timescales of hours to several days. Orbit-to-orbit variations are likely to occur. Based on the symmetry of the system one would expect that the IR flux at $\phi = 0.25$ is similar to that observed at $\phi = 0.75$. This does not seem to be the case. It turns out, however, that similar variations with orbital phase (i.e., maximum at $\phi = 0.5$ and minimum at $\phi = 0.75$) are observed for this system in other wavelength bands as well.

Kaper et al. (1990) reported the discovery of Raman-scattered emission lines in the UV spectrum of HD 153919. These lines originate from strong EUV emission lines in the spectrum of the X-ray source which are Raman scattered to UV wavelengths by He II ions in the stellar wind: a photon belonging to a strong emission line close to the He II Lyman-β transition (256Å) has a small probability of scattering via the far wing of the upper energy level of Lyman β to the corresponding downwards transition close to the He II Balmer-α line at 1640Å. In this way, the X-ray source's EUV spectrum can be observed at UV wavelengths. Raman scattering is commonly observed in symbiotic systems (cool supergiant with hot companion), but then the Lyman-β transition of hydrogen is involved (e.g., Schmid 1989). HMXBs can be seen as the hot-supergiant equivalents of symbiotic systems. The integrated flux (arbitrary units) of these Raman-scattered emission lines is plotted as a function of orbital phase in Fig. 3. It appears that these Raman lines reach maximum flux at $\phi = 0.5$ and seem to have disappeared around $\phi = 0.75$. This behaviour is most likely related to the partial obscuration of the X-ray source's soft spectrum as observed from the increasing X-ray hardness ratio at late orbital phases (Haberl et al. 1989).

It is tempting to conclude that the observed variation in the 11.5μm flux of HD 153919 is also related to the obscuration of the X-ray source at late orbital phases. It is not clear, however, how this might affect the infrared spectrum and how this would explain the observed dependence on orbital phase. The quenched stellar wind inside the Strömgren zone could produce a higher IR flux due to its relatively high density and low velocity. Alternatively, IR emission lines formed in the ionization zone might be responsible for the increase in IR flux. IR spectra are needed to discriminate between these two options. In either cases an asymmetry has to be introduced to explain the observed phase behaviour.

3. Wind Bow Shocks Around HMXBs

HMXBs evolve from massive, close binary systems. When the initially more massive star (the primary) becomes a supergiant and starts filling its Roche lobe, a phase of mass transfer occurs, rejuvenating the secondary that eventually becomes the more massive star in the system. The primary evolves into a helium star that leaves a neutron star (or a black hole) after a supernova explosion. When less than half of the total mass of the system is lost during this event, the system (now containing an OB star and a compact companion) remains bound (Blaauw 1961) and gets a kick velocity. The binary system then leaves the location where it was born. As soon as the secondary OB star evolves into a supergiant, accretion of its dense stellar wind onto the compact star will power a strong X-ray source. Thus the binary-evolution scenario predicts that all HMXBs are runaway systems.

When an OB star moves supersonically through the ISM, the interaction of its stellar wind with the ISM gives rise to a bow shock. Van Buren & McCray (1988) examined 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 IR emission peaks at 60μm and results from interstellar dust that is swept up by the bow shock and heated by the radiation field of the OB star. In a subsequent study, Van Buren et al. (1995) detected wind bow shocks around one-third of a sample of 188 candidate OB-runaway stars.

Recently, a wind bow shock has been discovered around the HMXB Vela X-1 (Kaper et al. 1997b) indicating the runaway nature of the system. This observation provides compelling evidence that Blaauw's scenario for the formation of runaway stars applies in at least one case. An ISOCAM image (8.0–15.0μm) clearly shows the extended bow-shock structure (Fig. 4). The distance between the B0.5 Ib star HD 77581 (not detected by IRAS) and the wind bow shock is about 1 arcmin ($\sim$0.5 pc). From the direction of motion one can deduce that Vela X-1 probably originates from the OB association Vel OB1. At the distance of Vel OB1 (1.8 kpc), the space velocity of Vela X-1 with respect to the OB association is about 50 km s^{-1}. This would mean that the supernova that produced the neutron star in Vela X-1 occured about 2–3 million years ago, which is consistent with the prediction of binary-evolution scenarios (Van Rensbergen et al. 1996).

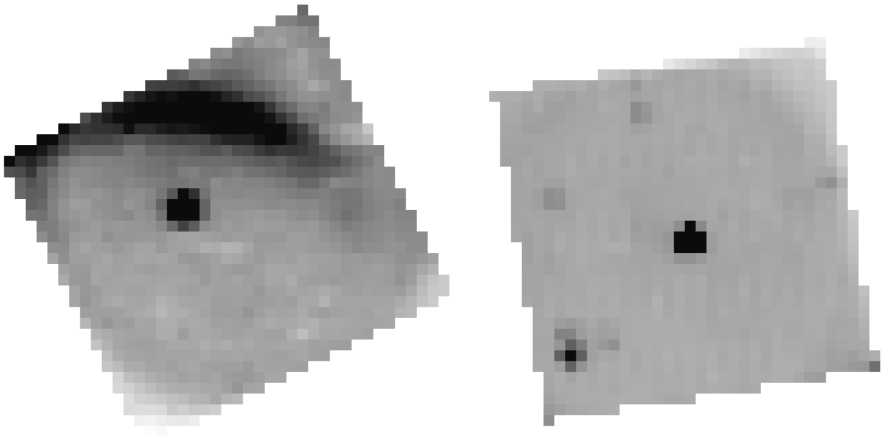

Figure 4. ISOCAM images obtained at 11.5μm of HD 77581/Vela X-1 (left, $\phi = 0.67$) and HD 153919/1700−37 (right, $\phi = 0.21$). North is up and east to the left; one pixel corresponds to 6 arcsec. The OB supergiant is detected in both cases. A wind bow shock is clearly resolved around HD 77581, but not around HD 153919.

We are presently investigating which fraction of the HMXBs are associated with bow shocks. Although HIPPARCOS data indicate that HD 153919 is a runaway system, a wind bow shock is not observed in the ISOCAM field of view (Fig. 4). For distant systems (for which no HIPPARCOS data are available), the shape of the bow shock can be used to determine the origin of the system. Identification of the 'parent' OB association provides an accurate estimate of the distance of the system. The derived kinematical age puts important constraints on binary evolution.

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Discussion

Conti: Can you remind me, what's the numerical definition of a 'runaway' velocity?

Kaper: Well, it was originally a 3-σ detection, so, if the average space velocity is 10 km s^{-1}, that's $\sim$30 km s^{-1}. In that sense, not all the stars I listed are 'official' runaways.

Owocki: I'm not sure I followed the full logic; in the press release I saw(!) you're saying that this actually proves the supernova-ejection scenario for Vela X-1? Or could it be a coincidence, that the system was ejected from a cluster through dynamical interactions, and then subsequently the supernova went off?

Kaper: Well, that's possible, of course; but then it would've been ejected as a binary, and there are only about 3 such binary runaways. Here you also have the originating OB association identified – that doesn't rule out a dynamical interaction, but we do know for sure that a supernova has gone off in the system.

Dufton: Don't the simulations show that you very rarely get binaries ejected from clusters through dynamical interactions?

Kaper: Yes, and that seems to be supported by the observations.

Maeder: It's remarkable that these runaway stars very often have high rotational velocities. The idea is that matter coming from the supernova imparts angular momentum, and at the same time enriches the companion's surface helium? Then it would be very interesting to look for other elements coming from the supernova.

Kaper: No, only a *very* small fraction of the supernova mass is intercepted by the companion. It is the mass-transfer process just *before* the eruption that is important. The mass donor at that stage could be helium rich.

Gies: Peter Leonard wrote a paper, I think in Monthly Notices, where he said that some binary–binary dynamical interactions could involve actual collisions, and he proposed that this could lead to some additional angular-momentum transfer and perhaps extra mixing. So the dynamical model might lead to high rotational velocities and surface helium abundances, as well as Blaauw's traditional supernova model.

I think there's now good evidence for both scenarios. Your work with Vela X-1 has beautifully shown that at least some of these X-ray binaries are clearly runaway objects, but there are also runaway binaries, such as Y Cyg and HD 1337, and it's very hard to see how you could get those in the supernova scenario. Clearly, Nature lets both mechanisms operate.

Langer: Looking at the space velocities, they're not all that impressive. Are they consistent with simple mechanical arguments of the momentum transfer in supernova explosions?

Kaper: Well, you expect to get something that's about the orbital velocity. Most of the systems here are Be-type X-ray binaries, so you might expect lower runaway velocities than for the high-mass, OB X-ray binaries.

Conti: Just looking at that old binary-evolution scenario you showed at the beginning, I wondered what sort of supernova is produced by a massive helium star?

Kaper: Do you mind if I just rephrase your question a little bit? Because a very interesting point is what happens if a black hole is formed; then a lot of material that might otherwise be lost is caught by the black hole. Cygnus X-1 really seems to be a runaway system, and tells us something about what must happen to the supernova.