

BOW SHOCKS AROUND RUNAWAY STARS. III. THE HIGH RESOLUTION MAPS

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ABSTRACT

In a recent survey for bow shock structures around OB runaway stars using the ISSA/IRAS archival data and excess maps at $60\ \mu\text{m}$, 58 candidates were found. These objects are surrounded by extended infrared emission at $60\ \mu\text{m}$, characteristic of warm dust heated by ultraviolet photons, a signature of wind bow shocks. High resolution IRAS (HiRes) images have been produced for these 58 objects and some of those spatially resolved are presented in this study. The images were used to distinguish between multiple confused IR sources, possible artifacts and unambiguous bow shocks, as the sources of the extended $60\ \mu\text{m}$ emission. Six new bow shocks have been identified using this method, and three have been rejected. Twenty two of the targets, however, remain spatially unresolved even at the nominal HiRes resolution of $\sim 1'$. For the larger and better defined bow shocks some internal substructure is discernible. The length of these features suggest that they arise as the result of a subtle dynamical instability. It cannot be ruled out, however, that some of the bow shock morphology could be imprinted by the surrounding medium. © 1997 American Astronomical Society. [S0004-6256(97)03502-4]

1. INTRODUCTION

In a recent search for bow shock structures, IRAS data for 188 nearby runaway stars was presented (Van Buren *et al.* 1995, hereafter Paper II). The bow shocks around runaway stars were first identified in the infrared by Van Buren & McCray (1988, hereafter Paper I), and they arise when their stellar winds become confined by ram pressure due to their supersonic motion through the interstellar medium (see, e.g., Van Buren & Mac Low 1992). Their sizes, luminosities and color temperatures can be explained with simple analytical models, based on the momentum balance between the star's wind and the ram pressure from the ISM, and radiative heating of the swept-up dust by the OB star. For some of the prototypical objects the IRAS observables are well reproduced (Paper I). The bow shock model has been also applied to explain the kinematics and axisymmetric morphology of cometary H II regions (Van Buren *et al.* 1990; Mac Low *et al.* 1991).

In Paper II a robust method was developed to distinguish low surface brightness extended regions against a cooler background in the IRAS data. The basic idea consists of the removal of the background radiation in the 12, 25, and $60\ \mu\text{m}$ bands based on a linear scaling of their $100\ \mu\text{m}$ radiation. These maps are then left only with the *excess* emission above a mean background. These excess maps are better than color temperature or ratio maps because they are insensitive to zero-point errors, and continue to work in areas of high background.

In the present study the IRAS high resolution (HiRes) im-

ages for the 58 candidates from the original survey (Paper II) are analyzed. The goal is to identify, based on their morphology, new resolved bow shock structures. A larger sample of bow shocks is a necessary step towards a better understanding of their pre/post shock conditions, the physics of the shock interaction, the properties of the dust emissivity, and the gas-to-dust ratio in these regions.

The HiRes maps or images are discussed in Sec. 2. The likely bow shocks and the other objects are presented in Sec. 3; and Sec. 4 contains the concluding remarks.

2. THE IRAS HIRES IMAGES

The high resolution maps are obtained by processing the IRAS survey data over a specific region with a *maximum correlation* algorithm, which improves the spatial resolution down to $\sim 1'$ in the best conditions (Aumann, Fowler & Melnyk 1990; Cao *et al.* 1996). The maps are obtained by iteration of the above procedure 1, 5, 10, and 20 times. Tests have shown that photometry is preserved at the 20% level (see, e.g., Levine 1993). The images have a size of $60' \times 60'$ with a plate scale of $15''$ per pixel. All the images presented in this study are at the $60\ \mu\text{m}$ IRAS band, where the far infrared signal of the radiatively heated dusty bow shock is the strongest (although the data for the other three IRAS bands were also analyzed).

One important thing to keep in mind is that these maps can not substitute or provide the same information as the excess maps. The excess maps remove most of the background cirrus emission and reveal the "excess" emission at the corresponding wavelength band. The HiRes images provide a higher spatial resolution than the excess maps and undergo an extensive processing (Fowler & Aumann 1994), but do not remove the effects of the cooler background.

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TABLE 1. Bow shock and/or excess around runaway stars.

(1) Star	(2) SpType	(3) Name	(4) Type ^a
HD1337	O9III ⁿⁿ +	...	no
HD2905 ^b	B1Iae	κ Cas	▷
HD4142	B5V	...	●
HD17505	O6e	...	○?
HD19374	B1.5V	...	●
HD19820	O9IV	...	▷?
HD22928 ^b	B5III	δ Per	▷
HD24431	O9IV-V	...	●
HD30614 ^b	O9.5Iae	α Cam	▷
HD34078	O9.5Ve...	...	●
BD+39 1328	O9III:	...	●
HD36862 ^b	B0.5V	λ Ori	▷
HD37020	O7	...	●
HD37737	B0II:	...	○?
HD41161	O8V	...	▷
HD41997	O7	...	●
HD42933 ^b	B3III+	δ Pic	▷
HD47839	O7Ve	...	no
HD48099	O6e	...	▷
HD50896 ^b	WN	S308	○
HD52533	O9V	...	●
HD54662	O7III	...	▷
HD57061 ^b	O9 Ib	τ CMa	▷
HD64315	O6e	...	●
HD66811	O5Ia...	...	●
HD89137	B2II	...	●
HD92206	O6	...	●
HD101131	O7n	...	●
HD112244	O9Ibe	...	●
HD130298	O5/O6	...	▷
HD135240	O8.5V	...	●
HD329905	O+	...	●
HD143275 ^b	B0.2IV	δ Sco	▷
HD149757 ^b	O9V	ζ Oph	▷
HD156212	O+	...	no
HD158186	O9.5V	...	●
HD64492	O6	...	●
HD169582	O5e	...	▷
HD171491 ^b	B5	...	●
HD175514	O8:Vnn	...	▷
HD186980	O7.5III:	...	●
HD188001	O8e	...	▷
HD227018	O7	...	●
HD189957	B0III	...	●
HD192163 ^b	WNn...	NGC 6888	○
HD195592 ^b	O9.5Ia	...	▷
BD+43 3654 ^b	B	U824	▷
HD199579	O6Ve	...	●
HD202214	B0II	...	●
HD203064	O8e	...	●
HD203467 ^b	B3IVe	6 Cep	▷
HD207538	B0V	...	●
HD210839 ^b	O6Iab:...	λ Cep	▷
HD212593	B9Iab	...	●
HD213087	B0.5Ibe...	...	●
HD214680	O9V	...	▷?
BD+63 1964	B0II	...	●
HD224151	B0.5IIvar	...	●

^a▷=bow shock, ○=bubble, ●=excess^bFrom Paper I

The results from the HiRes images are summarized in Table 1, including those objects (fifteen) already identified in Paper I. The table indicates explicitly the new likely bow shocks, and follows the same classification scheme of Papers

I-II. For objects with a resolved extended structure a “▷” for a bow shock or a “○” for a bubble are assigned. In those cases where the source remains unresolved a “●” is used to indicate their excess 60 μ m emission. Nearly half of the 58 original targets still belong to this category.

The new likely bow shocks are shown in Fig. 1 and correspond to HD 48099, HD 175514, HD 188001, HD 130298, HD 41161, and HD 54662. As an example of how difficult is to decide whether the 60 μ m emission defines or not a bow shock, the images of HD 19820 and HD 214680 (borderline cases) are also shown. All the images are centered at the position of the runaway star, which in most cases does not appear at 60 μ m. The HD 41161 and HD 214680 objects do not resemble the classical arc-like structures, but the magnitude and direction of their motion are consistent with this hypothesis (see, e.g., Paper II).

3. THE BOW SHOCK SUBSTRUCTURE

3.1 Instabilities for Bow Shocks around OB Runaways

The bow shocks associated with α Cam and ζ Oph look structureless at the spatial resolution of the ISSA/IRAS maps. Indeed at the $\sim 1''.5$ per pixel resolution of the maps, these objects closely resemble the predicted shape for an ideal momentum conserving wind-ISM interacting bow shock (Baranov *et al.* 1971; Wilkin 1996). It is at the enhance resolution of the HiRes images that some large substructure becomes discernible (see Fig. 2).

We have shown previously that for the bow shocks around runaway OB stars, through analytical and numerical simulations (Dgani *et al.* 1996a, 1996b), a dynamical instability is a plausible explanation for the long wavelength substructure observed. The models rely on two assumptions: that the bow shock is contained between two nearly isothermal shocks, and that dust heated IRAS emission describes the gas density inside the bow shock. If this is the case, then variations in the flow perpendicular to the surface can disturb it, becoming unstable. The faster growing modes of this *transverse acceleration instability* (TAI) have wavelengths which are a fraction ($\sim 1/10 - 1/5$) of the arc-length of the bow shock (Dgani *et al.* 1996a, 1996b). The only other competing instability for a thin layer bounded by two isothermal shocks is a ‘non-linear thin shell instability’ (NTSI) describe by Vishniac (1994). In the NTSI the faster growing modes have wavelengths which are comparable to the thickness of the shell, and therefore, a lot smaller than the bow shock’s arc. In the wind bow shocks around runaway stars it may be the case that near the stagnation point the NTSI dominates and provides the seed for the TAI (see Dgani *et al.* 1996a, 1996b).

The effects of a TAI on the wind bow shocks around OB stars are less dramatic than those predicted by the numerical simulations of Wolf-Rayet (WR) bubbles in motion (see, e.g. Brighenti & D’Ercole 1995a, 1995b). For the WR bow shocks the NTSI is a key process to understand the rich structure they obtained. One of the predictions of the TAI model is that the degree of substructure depends on the ratio of the wind velocity with respect to that of motion either from the star itself or the ambient medium. Essentially the bow shocks are more stable for a high velocity wind, where

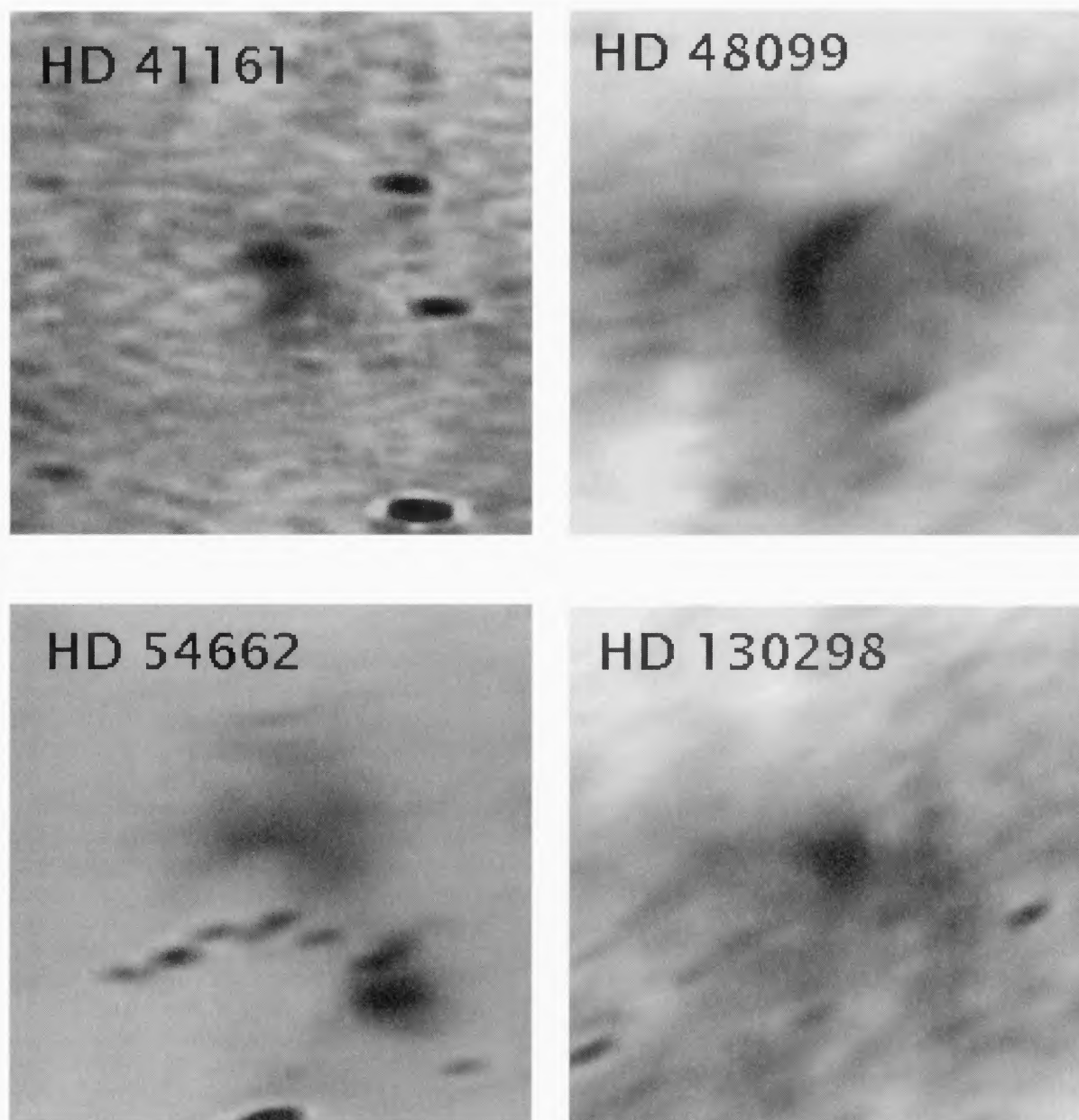


FIG. 1. The 5th iteration greyscale maps at $60\ \mu\text{m}$ for the new resolved bow shocks (with the high intensity regions being dark). The images are centered on the coordinates of stars: HD 41161, HD 48099, HD 54662, HD 130298, HD 175514, and HD 188001. The two other promising candidates HD 19820 and HD 214680 are also shown. Displayed too are HD 17505 and HD 37737, which are apparently engulfed by bubbles. All the fields are one arc degree (North is up; East is left).

the surface density of the shell is dominated by the mass of the interstellar medium and not by that of the wind (momentum conservation). This is precisely the case for the bow shocks associated with runaway early-type stars, with typical wind velocities of $\sim 500\text{--}3000\ \text{km s}^{-1}$ and mass loss rates $\sim 10^{-5}\text{--}10^{-6}\ M_{\odot}\ \text{yr}^{-1}$ (see, e.g., Puls *et al.* 1996).

The large physical size of the wind bow shocks, a few parsecs, brings into play another possibilities for their substructure: the inhomogeneities of the surrounding circumstellar medium, and the large scale effects of a magnetic field. These processes have to be considered if one wants to understand the morphology of the α Cam bow shock. This object is apparently made up by two enormous crossing or

nested arcs and it is difficult to envisage that they are the result of a local instability process (see Fig. 2).

3.2 The Signature of Artifacts

One of the main concerns for any process which tries to enhance the spatial resolution of an image is the creation of spurious structure. There are a variety of well known artifacts that appear during the HiRes processing of images: ringing, blank pixels-coverage depletion, aliasing and striping (see, e.g., Cao *et al.* 1996). In most situations, however, these artifacts are easily recognizable.

Given the large extent of some of the wind bow shocks,

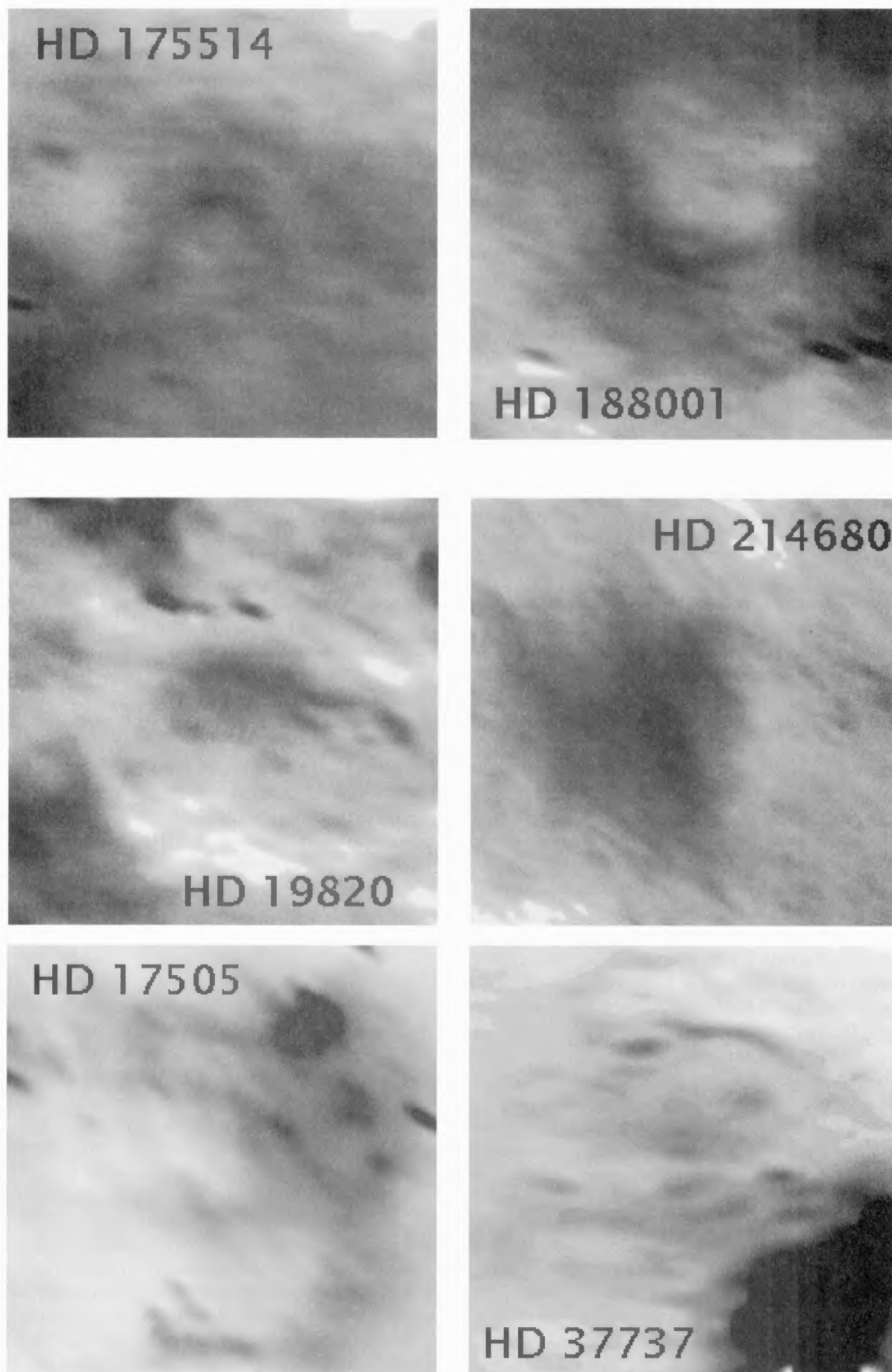


FIG. 1. (continued)

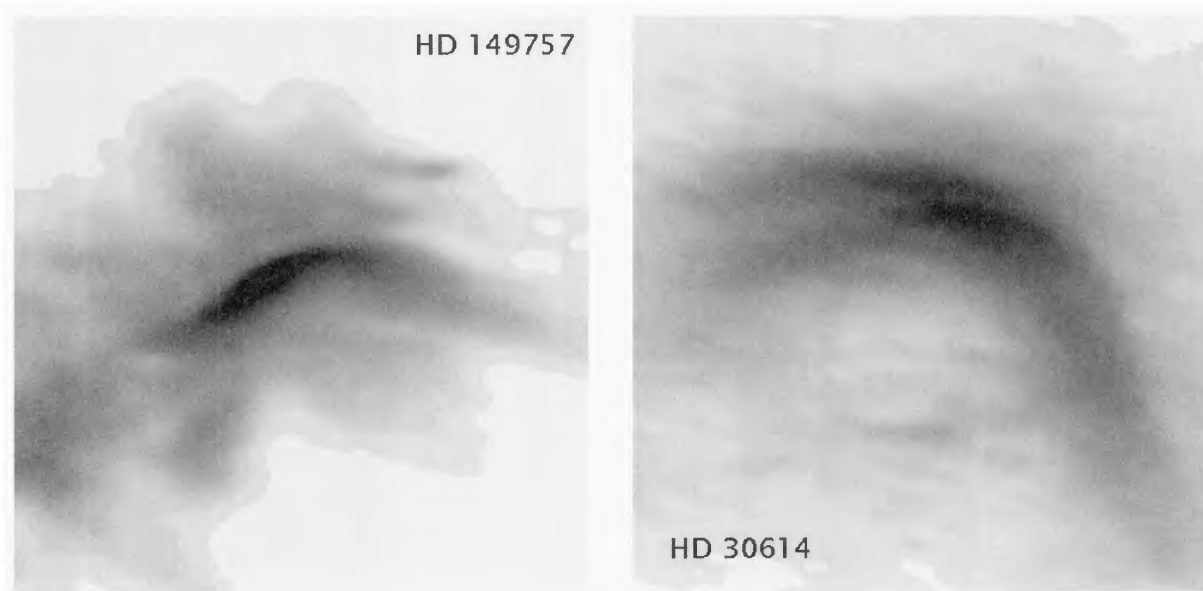


FIG. 2. The 5th iteration HiRes image of the bow shock structure associated with ζ Oph (HD 149757) star and α Cam (HD 30614). The lower iteration maps already show some subtle clumpy structure in the outer regions of the bow shocks.

which covers almost the one degree field of the HiRes images, it becomes important to evaluate the signature of the artifacts at these scales. To do this a series of simulations were run of morphological shapes with curvatures and intensity contrasts similar to those observed in the bow shocks. The idea was to subject these models to the same HiRes reconstruction process of the *IRAS* images, and to analyze in which way they were modified. The spatial enhancement is based on the capability of reconstructing an image using a simulated beam (Fowler & Aumann 1994). This procedure allows to put in *an arbitrary source distribution shape* and to run it through the same process as a standard image. One of the most compelling examples comes from the 5th and 20th iteration maps of α Cam and a ring model. The ring model corresponds to a uniform intensity doughnut with sharp interior and exterior boundaries; these edges are a bit more steep than those in the real objects.

In Fig. 3 we show the 5th and 20th iterations maps for α Cam and the ring model. The analysis of ring model images indicate that the most significant changes take place at the edges and along the scanning direction (north-south). There is an increase of the intensity along these regions of $\sim 5\% - 15\%$, but the effect is spatially limited to a narrow band. This flux variation is well within the flux conservation error expected from the HiRes process, but certainly increases the relative brightness of the boundaries. Perpendicular to the scanning direction (east-west) the inner and outer edges of the ring are modified over a scale of approximately half of their diameter. In the 20th iteration map there is a short wavelength component which is superimposed to the edge variation and mimics a small clumpy substructure. Despite of all these changes in the model, the images of α Cam, which have undergone a similar process, do not show such a drastic variations. There is a concentration of flux along the borders, which brings up some of the features and enhances

the spatial resolution, but these are changes at the $\sim 5\%$ intensity level. Essentially in the α Cam images there are no similar large scale features as those which appear in the models after the HiRes processing. The arcs in α Cam are thought to superimpose or cross and they are well resolved features in the 25, 60, and 100 μm images, so we think they are real. There is the possibility that some short wavelength structure appears in a spurious manner in the high iteration maps. One should be cautious when interpreting these features are arising from dynamical or thermal instabilities. This effect is more noticeable in the 100 μm images (see Fig. 4), where small clumps appear in the bow shock in the 20th iteration map, even though the spatial resolution at 100 μm is lower than at 60 μm .

4. CONCLUSIONS

We have analyzed 58 bow shock candidates using high resolution images of the four *IRAS* bands focusing on the results from the 60 μm images, where the dust heated emission is enhanced. Fifteen of these objects were previously known to have bow shocks or bubbles around them (Paper I).

Six runaway stars are accompanied by previously unidentified bow shocks. There are two stars, HD 19820 and HD 214680, for which the HiRes images are not enough to define completely their structure, but they remain as promising candidates to have bow shocks. Another two stars, HD 17505 and HD 37737, reside in complex regions and they seem to be surrounded by large bubbles. The HiRes images indicate that in eleven of the original fifty eight targets (Paper II) the extended 60 μm emission is partially confused by the presence of multiple or bright nearby sources. The remaining twenty two objects continue to display an extended 60 μm emission at the HiRes spatial resolution, except for HD 1337, HD 47839, and HD 156212, which do not fall in

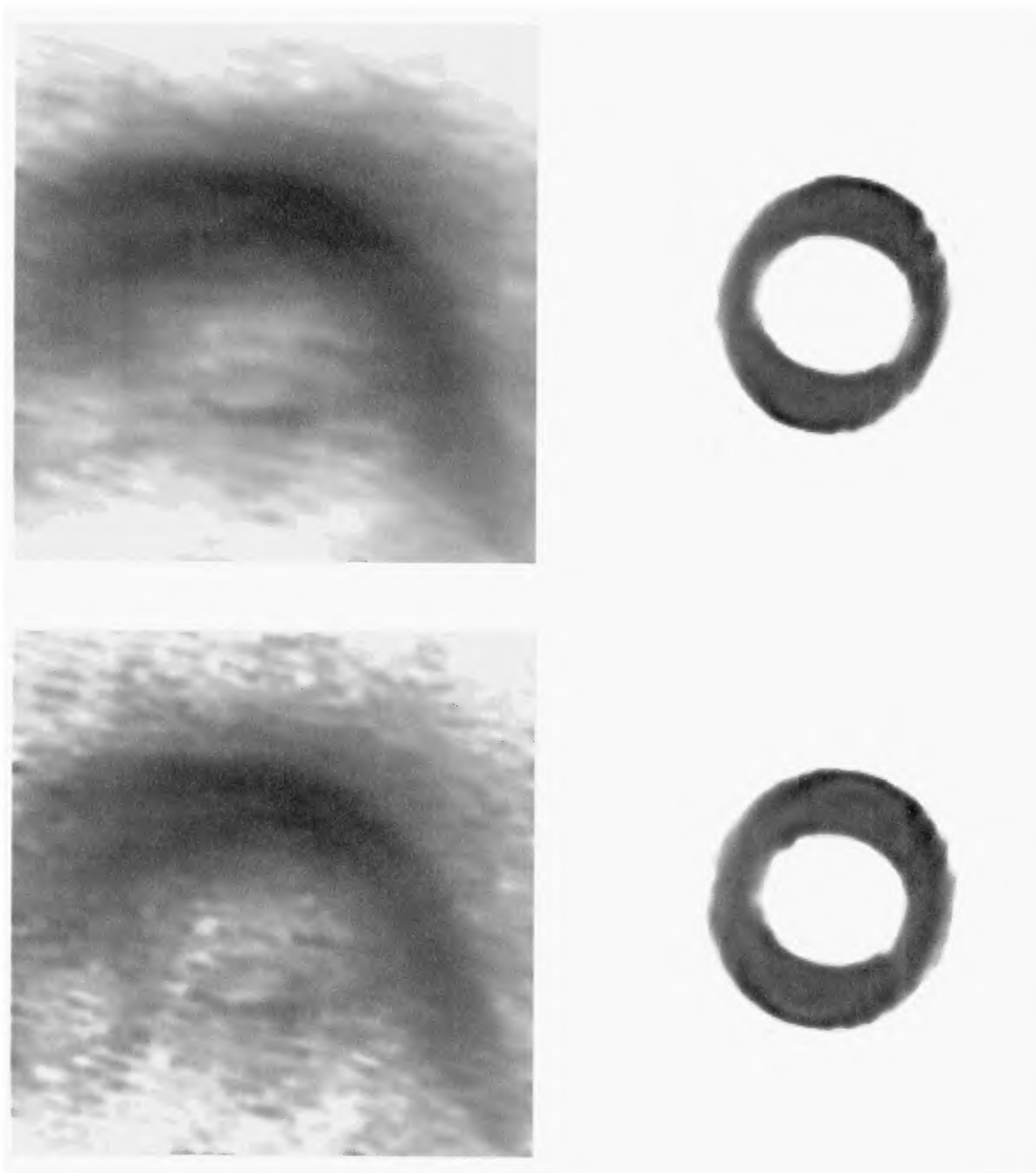


FIG. 3. The 5th and 20th iteration HiRes images at $60\ \mu\text{m}$ for the α Cam bow shock and the ring model. The images illustrate the possibility that spurious structure could be created by the HiRes process. Notice that α Cam bow shock, however, is not affected as much as the sharp edgy ring.

any of above categories. The emission and structure of these three objects seem to be randomly distributed, and therefore, have been dropped from the bow shock sample.

For two of the largest and better defined bow shocks HD 149757 (ζ Oph) and HD 30614 (α Cam) it is possible to distinguish some substructure along their rims. We suggest that the long wavelength of these features and their subtle appearance is consistent with a transverse acceleration instability. This instability arises by a disturbance driven by the flow perpendicular to the surface (Dgani *et al.* 1996a, 1996b). The NTSI is another process that has been invoked to explain the structure observed around the bow shocks of Wolf-Rayet stars (Brighenti & D'Ercole 1995a, 1995b). A detail comparison between the TAI and the NTSI in the con-

text of wind bow shocks around runaway OB stars is needed to understand their exact role (Blondin & Marks 1996). There are some large scale features in α Cam, nevertheless, which to be explained may require considering the effects of structure in the surrounding interstellar medium. Finally, there is a tendency in the high resolution process to create a short wavelength spurious structure in the high iteration maps in regions with sharp edges, which must be born in mind when interpreting some intensity clumps as instabilities.

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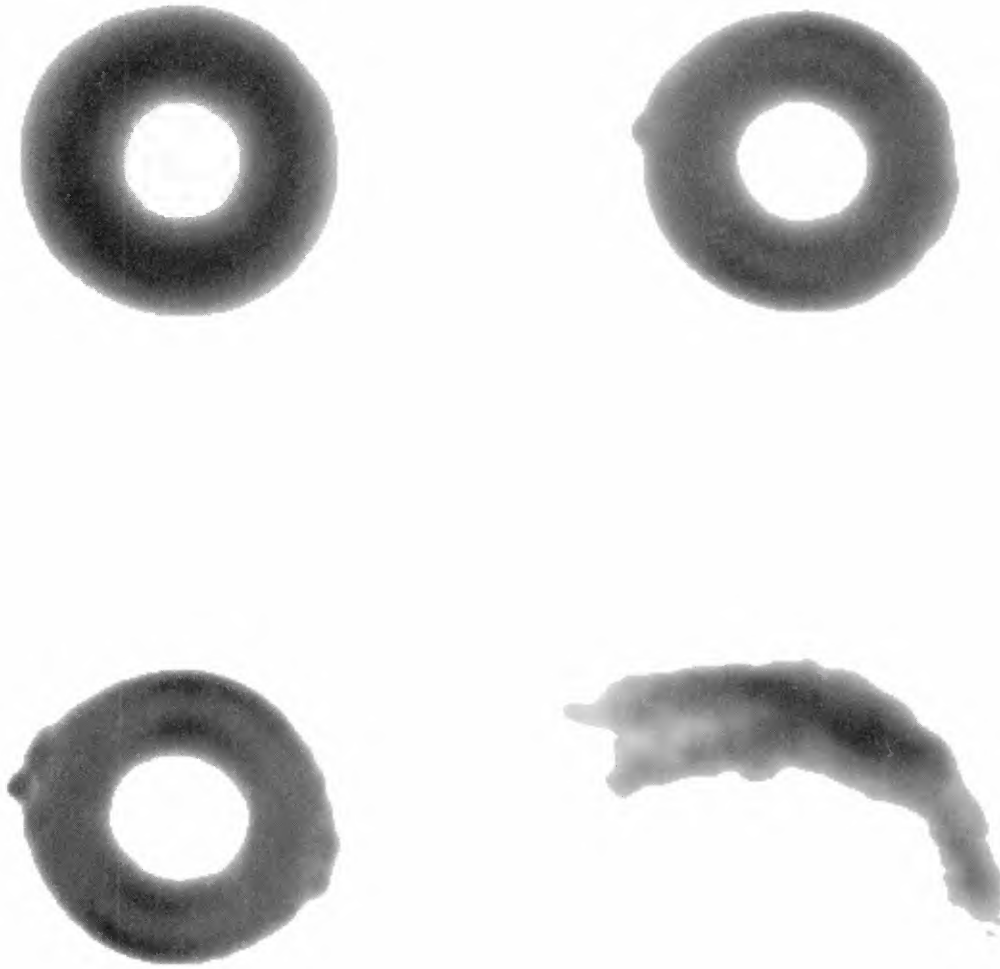


FIG. 4. HiRes maps can create short wavelength structures at a high number of iterations as illustrated in this sequence of images. The frames (a) through (c) correspond to a ring model in a beam simulation at $100\ \mu\text{m}$ for the first, 10th and 20th iteration. The α Cam image at $100\ \mu\text{m}$ after 20 iterations is also shown for comparison.

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