AKARI/FIS Mapping of the ISM-Wind Bow Shock around \( \alpha \) Ori

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Abstract

We present 10' \times 50' scan maps around an M supergiant \( \alpha \) Ori in at 65, 90, 140 and 160\( \mu \)m obtained with the AKARI Infrared Astronomy Satellite. Higher spatial resolution data with the exact analytic solution permit us to fit the de-projected shape of the stellar wind bow shock around \( \alpha \) Ori to have the stand-off distance of 4.8, position angle of 55° and inclination angle of 56°. The shape of the bow shock suggests that the peculiar velocity of \( \alpha \) Ori with respect to the local medium is \( v_p = 40 n_H^{3/2} \), where \( n_H \) is the hydrogen nucleus density at \( \alpha \) Ori. We find that the local medium is of \( n_H = 1.5 \) to \( 1.9 \) cm\(^{-3} \) and the velocity of the local flow is at 11 km s\(^{-1} \) by using the most recent astrometric solutions for \( \alpha \) Ori under the assumption that the local medium is moving away from the Orion OB 1 association. AKARI images may also reveal a vortex ring due to instabilities on the surface of the bow shock as demonstrated by numerical models. This research exemplifies the potential of AKARI All-Sky data as well as follow-up observations with Herschel Space Telescope and Stratospheric Observatory for Infrared Astronomy for this avenue of research in revealing the nature of interaction between the stellar wind and interstellar medium.

Key words: stars: individual (\( \alpha \) Ori) — stars: kinematics — stars: mass-loss — stars: supergiants — ISM: structure

1. Introduction

Alpha Orionis (Betelgeuse, HD 39801; hereafter \( \alpha \) Ori) is a supergiant of spectral type M2 Iab: and is a very bright far-infrared (far-IR) source. Some extended structure in the far-IR was recognized around \( \alpha \) Ori in at 65, 90, 140 and 160\( \mu \)m obtained by using the most recent astrometric solutions for \( \alpha \) Ori. The arc-shaped structure at the interface between the stellar wind and the local interstellar medium (ISM).

Such structures can be formed around mass-losing stars at which the ram pressure of the ambient ISM balances with that of the stellar wind. These stellar wind bow shock arcs had already been found around hotter, more luminous OB stars in the IRAS All-Sky maps (Van Buren & McCray 1988). Most recently, Ueta et al. (2006) discovered a stellar wind bow shock arc around R Hya, an asymptotic giant branch star (an evolved star of lower mass and lower rate of mass loss), using the Spitzer Space Telescope.

Far-IR emission from these arcs is probably due mainly to thermal emission of cold dust components of the stellar wind bow shock whose temperature peaks at far-IR. There may be contribution from low-excitation atomic lines such as [O I] 63 \( \mu \)m, [O I] 145 \( \mu \)m and [C II] 158 \( \mu \)m at these wavelengths. However, the exact emission mechanism of these far-IR bow shocks remains unclear, while an attempt to identify their spectroscopic nature is currently on-going with the Spitzer Space Telescope. Meanwhile, theoretical studies have been done both analytically (Wilkin 1996; Wilkin 2000) and numerically (e.g. Mac Low et al. 1991; Dgani, Van Buren, & Noriega-Crespo 1996; Blondin & Koerwer 1998; Wareing, Zijlstra, & O’Brien 2007) and the structure of the stellar wind bow shocks has been understood reasonably well.

The AKARI Infrared Astronomy Satellite (AKARI; Muraikami et al. 2007) makes the All-Sky Survey in the far-IR for the first time in 25 years since IRAS at much
finer spatial resolution. The original IRAS images of α Ori allowed only rough identification of the shape of the extended far-IR emission (Stencel, Pesce, & Hagen Bauer 1988). The enhanced IRAS images of α Ori yielded just the mean radius and width of the arc with a rough estimate for the position angle of the apex (Noriega-Crespo et al. 1997). In this paper, we characterize the structure of the far-IR stellar wind bow shock around α Ori, using higher spatial-resolution AKARI images, and investigate the kinematics of the star, bow shock and ISM in the vicinity of the star by adopting the analytic solution of the bow shock (Wilkin 1996) and the most recent astrometric solutions for the star (Harper, Brown, & Guinan 2008).

2. Observations and Data Reduction

We observed α Ori in the four bands at 65, 90, 140 and 160 μm using the Far-IR Surveyor (FIS; Kawada et al. 2007) on-board the AKARI satellite (Murakami et al. 2007) on 2006 September 21 as part of the MLHES (“Excavating Mass Loss History in Extended Dust Shells of Evolved Stars”) Mission Program (PI: I. Yamamura). Observations were made with the FISO1 (compact source photometry) scan mode, in which two strips of forward and backward scans were done with a 70″ spacing at the 15″ s⁻¹ scan rate, resulting in the sky coverage of 10' × 50' centered at the target.

The FIS Slow-Scan Toolkit (Verdugo, Yamamura, & Pearson 2007; ver. 20070914) was used to reduce the data. We found that the quality of the resulting map was improved when we used a combination of the temporal median filter with the width of 200 s (or longer), temporal boxcar filter with the width of 90 s, and sigma clipping threshold of 1.5. For the reduction of data in the short wavelength bands (SW bands; 65 and 90 μm), the results were improved further when we performed flat-fielding using the local “blank” sky data. Furthermore, we applied a custom reduction process to remove pixel-dependent response variation by subtracting the baseline “sky value” from each pixel determined by a linear least-squares fit to the off-source pixel values in the time-series data.

The resulting maps are in 15 and 30″ pixel⁻¹ (default pixel scale) for the SW and LW (long wavelength; 140 and 160 μm) bands, respectively. The resulting 1 σ sensitivities are 4.0, 4.1, 6.5 and 19.7 MJy sr⁻¹ while achieving, on average, five, eight, 15, and 10 sky coverages per pixel were at 65, 90, 140 and 160 μm, respectively. The sky emission (the component removed during the reduction) is found to be 32.3 ± 4.6, 31.7 ± 3.5, 56.1 ± 5.8 and 81.4 ± 9.8 MJy sr⁻¹ at 65, 90, 140 and 160 μm, respectively. Photometry was done following the latest calibration method to address the effects due to slow transient response of the Ge:Ga detectors (Shirahata et al. 2008). Image characteristics are summarized in Table 1.

The measured sky emission values are consistent with the estimates obtained with the Spitzer Planning Observations Tool (SPOT) based on the COBE/DIRBE data (Reach 2000) in the wide bands at 90 and 140 μm (28.7 and 52.1 MJy sr⁻¹, respectively), while about 50% larger in the narrow bands at 65 and 160 μm (21.7 and 53.8 MJy sr⁻¹, respectively). By design, the spatial scale of the measured sky emission corresponds at most to the scan length (50’), which is comparable to the spatial resolution of the far-IR background data used in the SPOT background estimates (40’ to 70’; Reach 2000). Hence, good agreement between the measured and estimated sky emission values in the wide bands is reasonable. The 50% discrepancy in the narrow bands, on the other hand, may indicate highly structured and variable [OI] line emission at 63 and 146 μm in the background in the vicinity of α Ori, an oxygen-rich supergiant suffering from heavy mass loss. With our data, however, we are unable to either prove or disprove this possibility, unfortunately. Follow-up far-IR spectroscopic observations are indeed necessary.

3. Results

Figure 1 shows the background-subtracted false color AKARI/FIS scan maps of α Ori at 65 μm (N60; far left), 90 μm (WIDE-S; second from left), 140 μm (WIDE-L; second from right) and 160 μm (N160; far right). Surface brightness in MJy sr⁻¹ is indicated by the color scale that is specified in the wedge above each scan map. Due to the location of the detectors on the focal plane, the extent in the in-scan direction is different in each band. α Ori itself is clearly detected in all four bands. However, the 65 and 90 μm band maps are affected by pixel cross-talk induced by the bright star (linear extension of the star oriented at 64’ east of north) while the 160 μm band map is impacted by a ghost seen about 4’ southeast of the star (Kawada et al. 2007). The extended central emission core is the topic of our forthcoming paper and will not be discussed here.

Measured fluxes of the star (aperture defined by where surface brightness drops to the sky level) are 349 ± 11, 151 ± 4, 32 ± 1 and 49 ± 2 Jy at 65, 90, 140 and 160 μm, respectively. The flux values at 65 and 90 μm are consistent with the previous IRAS measurements (Noriega-Crespo et al. 1997). These values are obtained by following the standard method for point-source photometry including aperture correction elucidated in the Users Manual (Verdugo, Yamamura, & Pearson 2007), except for the last step in which the effects due to slow transient response of the Ge:Ga detectors is now addressed (Shirahata et al. 2008). The AKARI Ge:Ga detectors are known to underestimate the flux by roughly 60% due to slow transient response, and the latest calibration allows one to derive a correction factor via a power-law function of the total flux (source plus background) based on the calibration observations (Shirahata et al. 2008). Previously, the correction factors were assumed to be constants.

Besides the central star, the arc and bar are also clearly detected in a much finer spatial scale than in the previous IRAS maps (Noriega-Crespo et al. 1997), even though the scan width was not wide enough to capture these struc-

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1 The effective beam size of AKARI (0′5 to 0′9) is much smaller than that of IRAS (2′0 to 5′0).
2 Available at http://www.ir.isas.jaxa.jp/AKARI/Observation/
tures in their entirety. Additional scans to cover the whole arc were scheduled on 2007 September 21. Unfortunately, cryogenic liquid Helium boiled off on 2007 August 26 and we were unable to obtain the additional data. While detailed analysis of the structure of the arc has to wait until the All-Sky data become available, we can still make use of the data at hand.

The arc is distinctly visible to the north and southeast of the star in the 65 and 90μm band maps and is marginally discernible in the 140μm band map. In the 160μm band map, however, the arc is blended in with the background cirrus and is not cleanly distinguishable. The bar, on the other hand, can be seen in all four maps, while the structure becomes progressively less well-defined at longer wavelengths. In the SW band images, surface brightness of the brightest parts of the arc (northeast of the star; 20 to 25 MJy sr\(^{-1}\)) is higher than that of the bar (∼10 MJy sr\(^{-1}\)). In the LW band images, however, surface brightness of the bar (15 to 20 MJy sr\(^{-1}\)) is higher than that of the arc (5 to 10 MJy sr\(^{-1}\)).

Assuming that emission from the arc and bar detected in these maps is mainly due to thermal emission of optically-thin concentration of dust grains, we can estimate the dust temperature by fitting the observed surface brightnesses at these bands to a Planck curve (i.e., \(S_\nu \propto \tau_\nu (\nu_0/\nu)^\beta B_\nu (T_{\text{dust}})\)) where \(\gamma_\nu = \tau_\nu (\nu_0/\nu)^\beta\) is the optical depth at \(\nu\) power-law scaled from \(\tau_0\) at \(\nu_0\) with an index \(\beta\). \(B_\nu\) is the Planck function at \(\nu\) and \(T_{\text{dust}}\) is the dust temperature.

Instead of treating \(\beta\) as a free parameter, we varied it between 1 and 2 to see how \(T_{\text{dust}}\) and \(\tau_0\) would behave. We find 42 ± 9 K near the brightest parts to 11 ± 1 K near the edge of the arc and 22 ± 5 K in the bar. For the optical depth, we find values on the order of 10\(^{-5}\) to 5 × 10\(^{-4}\) typically with a factor of ∼2 uncertainty. The optical depth in the arc is generally about an order of magnitude lower than in the bar. Table 2 summarizes the observed characteristics of the arc, bar and background sky.

### 4. The Stellar Wind Bow Shock

#### 4.1. Orientation of the Bow Shock Cone

The far-IR arc around α Ori has been interpreted as the interface between the interstellar medium (ISM) and the circumstellar envelope developed by the stellar wind (Stencel, Pesce, & Hagen Bauer 1988; Noriega-Crespo et al. 1997) at which the ram pressure of the ambient ISM balances with that of the stellar wind, as has been found around OB stars (Van Buren & McCray 1988). The shape of such bow-shock arcs has been shown to follows the curve \(z = r^2/3R_0\) (where \(R_0\) is the stand-off distance between the star and the apex of the bow and \(r\) is the distance of the bow from the symmetric \(z\) axis of the bow) both numerically (Mac Low et al. 1991) and analytically (Wilkin 1996).

The shape of the arc around α Ori, however, appears to be much more circular. If one traces the brightness peak of the arc to fit an ellipse, one can predict how the bow appears in the plane of the sky assuming that (i) far-IR emission is mainly due to thermal dust emission, (ii) the shell is optically thin to far-IR light and (iii) the column density of dust is the highest where the bow intersects with an axisymmetric bow shock cone, we can fit the brightness peak of the arc to this solution.

For a given set of the stand-off distance and inclination and position angles of the bow (these angles define the 3-D orientation of the bow), one can predict how the bow appears in the plane of the sky assuming that (i) far-IR emission is mainly due to thermal dust emission, (ii) the shell is optically thin to far-IR light and (iii) the column density of dust is the highest where the bow intersects...
with the plane of the sky. Dust radiative transfer calculations in the circumstellar shells have shown that the above assumption (iii) is generally valid as long as the assumption (ii) is valid (e.g. Ueta et al. 2001; Ueta & Meixner 2003).

Then, one can quantify the difference of the prediction from the data by computing the inverse of the sum of the squares of the differences between the distance from the star to the arc peak and that from the star to the predicted positions of the arc. Since this quantity represents the “correlation” between the data and prediction, it tends to be small if the prediction differs from what the data suggest. Thus, one can find the best-fit parameter set by locating the point in the parameter space at which this quantity becomes the largest.

Through this method, we find the stand-off distance (de-projected) to be $4.8 \pm 0.1\,\text{rad}$, the position angle to be $55^\circ \pm 2^\circ$ and the inclination angle to be $56^\circ \pm 4^\circ$. The uncertainties stem from those in determining the brightness peak of the arc by fitting the Gaussian to the surface brightness profile of the 90\,$\mu$m map, in which the arc is the most well-defined. Figure 2 shows the position of the apex of the best-fit bow shock cone projected in the plane of the sky.

The position angle is consistent with what has been concluded from lower resolution IRAS maps ($60^\circ \pm 10^\circ$; Noriega-Crespo et al. 1997) and is now more accurately determined with higher resolution AKARI maps. Adopting the heliocentric radial velocity of $v_{\text{rad}} = +20.7 \pm 0.4$ km s$^{-1}$ (the mean of the measurements made by Jones (1928) and Sanford (1933) as used by Harper, Brown, & Guinan (2008)), we see that the bow shock cone is oriented into the plane of the sky, unlike the previous studies assumed to be close to edge-on (e.g. Noriega-Crespo et al. 1997; Harper, Brown, & Guinan 2008). This is the first observational determination of the inclination angle of a stellar wind bow shock, owing to higher resolution AKARI maps.

4.2. Space Velocity of $\alpha$ Ori

The stand-off distance is determined by the ram pressure balance of the wind and ambient ISM. Therefore, starting from the pressure balance equation $\rho_{\text{w}} v_{\text{w}}^2 = \rho v^2_{\text{s}}$, one can determine the stand-off distance for a star that loses mass via an isotropic stellar wind of velocity $v_{\text{w}}$ and mass-loss rate $M$ while traveling through the ISM of a uniform density $\rho$ at velocity $v_s$, the stand-off distance is

$$R_0 = \frac{\sqrt{M v_w}}{4\pi \rho v_s^2}. \quad (2)$$

(Wilkin 1996). For $\alpha$ Ori, we have fairly well-established estimates for $M = 3.1 \pm 1.3 \times 10^{-6}$ $M_\odot$ yr$^{-1}$ (Harper, Brown, & Lim 2001) and $v_{\text{w}} = 17 \pm 1$ km s$^{-1}$ (Bernat et al. 1979). Also, Harper, Brown, & Guinan (2008) have derived the new distance of $197 \pm 45$ pc to $\alpha$ Ori based on astrometric solutions obtained by combining Hipparcos data with multi-epoch, multi-wavelength VLA radio positions.

Using these values, the de-projected stand-off distance $R_0$ is $8.5 \pm 1.9 \times 10^{17}$ cm. By keeping the interstellar hydrogen nucleus density at $\alpha$ Ori, $n_H$, as a free parameter, the peculiar velocity of the star with respect to the ISM in the vicinity of $\alpha$ Ori is

$$v_s = \sqrt{\frac{M v_w}{4\pi \mu H n_H R_0^2}} = (40 \pm 9) n_H^{-1/2} \text{ (km s}^{-1} \text{)} \quad (3)$$

where $\mu_H$ is the mean nucleus number per hydrogen nucleus for local medium ($\sim 1.4$) and $n_H$ is the mass of hydrogen nucleus.

Given the orientation of the bow shock cone, the peculiar velocity of the star with respect to the ISM in the vicinity $\alpha$ Ori can be decomposed into each of the equatorial space-velocity components (the radial direction, the direction in right ascension corrected for declination and the direction in declination) as

$$\begin{bmatrix} v_p \\ v_\alpha \\ v_\delta \end{bmatrix}_\alpha \text{ Ori} = \begin{bmatrix} 33 \pm 8 \\ 18 \pm 5 \\ 13 \pm 3 \end{bmatrix} n_H^{-1/2} \text{ (km s}^{-1} \text{)} \quad (4)$$

These values can be converted to the Galactic space-velocity components ($U$, $V$ and $W$ where they are positive in the directions of the Galactic center, Galactic rotation and the North Galactic Pole, respectively) through a spherical trigonometric transformation (e.g. Johnson & Soderblom 1987) as

$$\begin{bmatrix} U \\ V \\ W \end{bmatrix}_\alpha \text{ Ori ISM} = \begin{bmatrix} -34 \pm 8 \\ -10 \pm 4 \\ +17 \pm 5 \end{bmatrix} n_H^{-1/2} \text{ (km s}^{-1} \text{)} \quad (5)$$

Since these values are based purely on the orientation of the bow shock cone, they represent the Galactic space-velocity components of $\alpha$ Ori with respect to the ISM in the vicinity of $\alpha$ Ori. Here, the superscript to the $[U,V,W]$ vector indicates what velocity it refers to while the subscript refers to with respect to what the velocity is defined.

4.3. ISM Flow in the Vicinity of $\alpha$ Ori

The new astrometric solutions by Harper, Brown, & Guinan (2008) yield the heliocentric Galactic space-velocity components of $\alpha$ Ori as

$$\begin{bmatrix} U \\ V \\ W \end{bmatrix}_\odot = \begin{bmatrix} -22 \pm 1 \\ -12 \pm 3 \\ +21 \pm 4 \end{bmatrix} \text{ (km s}^{-1} \text{)} \quad (6)$$

Thus, by combining the above two sets of values we can compute the heliocentric Galactic space-velocity components of the ISM in the vicinity of $\alpha$ Ori as

$$\begin{bmatrix} U \\ V \\ W \end{bmatrix}_\odot = \begin{bmatrix} -22 \pm 1 \\ -12 \pm 3 \\ +21 \pm 4 \end{bmatrix} - \begin{bmatrix} -34 \pm 8 \\ -10 \pm 4 \\ +17 \pm 5 \end{bmatrix} n_H^{-1/2} \text{ (km s}^{-1} \text{)} \quad (7)$$

Hence, the stellar wind bow shock around $\alpha$ Ori is a consequence of a mass-losing M supergiant moving in the ISM that flows in the direction specified by the above space-velocity vector.
This ISM flow around \( \alpha \) Ori must originate from somewhere in the vicinity of \( \alpha \) Ori. The most probable source of this ISM flow in the vicinity of \( \alpha \) Ori is undoubtedly the Orion OB1 association (Warren & Hesser 1977). Assuming that all four sub-associations (OB1a through OB1d) contribute equally to generate the ISM flow in the vicinity of \( \alpha \) Ori, one can define the flow vector toward \( \alpha \) Ori at \([X, Y, Z] = [-182, -66, -31 \text{ pc}]\) emanating from the mean position of the associations at \([X, Y, Z] = [-350, -170, -133 \text{ pc}]\).

Then, one can search for values of \( n_H \) that would align the ISM flow vector \([U, V, W]_{\alpha \text{ Ori ISM}}\) with this flow from the Orion OB1 association within the quoted uncertainties in Eq. 7. Possible values of \( n_H \) turns out to be 1.5 to 1.9 \( \text{cm}^{-3} \). These values are higher than \( n_H \approx 0.3 \text{ cm}^{-3} \) estimated for material in front of the Orion OB association (Frisch, Sembach, & York 1990). In the direction of \( \alpha \) Ori, however, the H\( I \) column density is estimated to be \( 0.27 \times 10^{22} \text{ cm}^{-2} \) (Kalberla et al. 2005), implying \( < n_H > = 4.4 \text{ cm}^{-3} \) for the distance of 197 pc. Thus, our estimate of \( n_H \) may not be too large.

The heliocentric Galactic space-velocity components of the ISM flow in the vicinity of \( \alpha \) Ori can be converted back to the equatorial space-velocity components through an inverse spherical trigonometric transformation as

\[
\begin{bmatrix}
  v_p \\
  v_\alpha \\
  v_\delta
\end{bmatrix}_{\alpha \text{ Ori ISM}} = \begin{bmatrix}
  21 - 33 n_H^{-1/2} \\
  23 - 18 n_H^{-1/2} \\
  9 - 13 n_H^{-1/2}
\end{bmatrix} \text{ (km s}^{-1}\text{)} \\
\]

and for \( n_H = 1.5 \text{ to 1.9 cm}^{-3} \)

\[
\begin{bmatrix}
  v_p \\
  v_\alpha \\
  v_\delta
\end{bmatrix}_{\alpha \text{ Ori ISM}} = \begin{bmatrix}
  -6 \text{ to } -3 \\
  9 \text{ to } 10 \\
  -1 \text{ to } 0
\end{bmatrix} \text{ (km s}^{-1}\text{)} \\
\]

Thus, the ISM around \( \alpha \) Ori flows at about 11 km s\(^{-1}\) into the position angle of \( \sim 95^\circ \) out of the plane of the sky (toward us).

Since the stellar wind bow shock is a consequence of the peculiar motion of the star and the ISM flow at the star, the apparent orientation of the bow shock would not necessarily yield information on both. When the direction of the proper motion is aligned with the direction of the apex of the bow, the ISM at the star is stationary with respect to the Sun or flows against the peculiar motion of the star. On the other hand, when the direction of the proper motion is not aligned with the direction of the apex of the bow, the ISM at the star probably flows obliquely with respect to the peculiar motion of the star. Therefore, direct comparison of the orientation of the bow with respect to the direction of the peculiar motion of the star would provide a reasonable diagnostic for the presence and direction of the ISM flow around the star.

4.4. Substructure of the Bow Shock

For the derived values of \( n_H = 1.5 \text{ to } 1.9 \text{ cm}^{-3} \), the corresponding peculiar velocity of the star with respect to the ISM in the vicinity of \( \alpha \) Ori is 33 to 29 km s\(^{-1}\) (Eq.3). This means that the ratio of the peculiar velocity of the star to the wind velocity \((v_v/v_w)\) is 1.7 to 1.9. Thus, the bow shock may be prone to instability (Dgani, Van Buren, & Noriega-Crespo 1996; Blondin & Koerwer 1998) and may even develop vortices (e.g. Wareing, Zijlstra, & O’Brien 2007).

Figure 2 is a close-up of the northern part of the arc overlaid with a line that delineates the Wilkin (1996) analytic solution at the 55° position angle at the 47° inclination angle. In general the Wilkin curve predicts where the surface brightness peaks along the arc extremely well. However, as one follows the arc structure from the apex to the downstream direction, there is a discontinuity of surface brightness along the arc at the position angle \( \sim 0^\circ \) and a local enhancement of surface brightness at around \((0', 7')\) from the star. The position of this local brightness enhancement is somewhat interior to the Wilkin curve unlike other parts of the arc.

This drop of surface brightness accompanied by a local enhancement off the Wilkin curve may be due to vortex shedding caused by instabilities in the bow surface (Blondin & Koerwer 1998; Wareing, Zijlstra, & O’Brien 2007). In an isothermal bow shock, Blondin & Koerwer (1998) found that instabilities would manifest themselves as wiggles in the bow on the length scale of the stand-off distance. Figure 2 shows that reduction and enhancement of surface brightness occurs about the stand-off distance away from the apex. Qualitatively, the observed structure of the bow shock resembles to that of the numerical models showing vortex shedding and the development of vortex rings. Therefore, more detailed numerical investigations into the development of instabilities on the surface of the bow shock appears worthwhile.

4.5. The Bar ahead of the Bow Shock Cone

The existence of a linear bar structure ahead of \( \alpha \) Ori is intriguing. At the moment there is no evidence that indicates the bar being a (by)product of the interaction between the ISM and stellar wind from \( \alpha \) Ori or otherwise: the origin of the bar remains unclear. Similarly, there is no evidence that suggests the bar is co-spatial with \( \alpha \) Ori. However, our data (Table 2) show higher optical depths in the bar than in the arc and in the background. Moreover, the bar and background seem to have roughly the same optical depth values.

Thus, the bar appears to be more like the background cirrus than the arc, and hence, the bar is probably not caused by the interaction between the stellar wind and ISM. Also, assuming that these structures are made up with similar matter and have similar density, the differences in the optical depth suggests that the bar is extended along the line of sight like a sheet. If the bar represents a local concentration of matter co-spaced with \( \alpha \) Ori, the motion of the star and angular separation between the star and bar imply a collision between the two in about 3000 yr. Even if this is the case, it is still not clear whether the bar is caused by this ISM flow in this region or is caused by other external means (such as \( \lambda \) Ori).
5. Summary

AKARI/FIS scan maps around \( \alpha \) Ori \((10' \times 50')\) at 65, 90, 140 and 160\(\mu\)m are presented. These images show the extended emission core and most of the circumstellar arc plus the northern bar structure at much higher spatial scale than in the previously obtained IRAS maps. Spatial resolution of the data is good enough to define the structure of the arc to be fit with the exact analytic solution for stellar wind bow shocks, while the scan did not cover the arc in its entirety and there are some anomalies by pixel cross-talk in the SW band and by ghosting in the 160\(\mu\)m band due to the bright central star.

Rather circular appearance of the arc (eccentricity 0.02) suggests that the stellar wind bow shock cone of 4.8 de-projected stand-off distance is inclined at 56\(^\circ\) with respect to the plane of the sky and oriented at 55\(^\circ\) position angle (east of north). Adopting the distance of 197 pc, rate of mass loss at 3\(\left(\text{east of north}\right)\). Adopting the distance of 197 pc, rate of mass loss at 3.1 \(\times 10^{-6}\) \(M_\odot\) yr\(^{-1}\), and wind velocity of 17 km s\(^{-1}\), the peculiar velocity of the star with respect to the ISM at \(\alpha\) Ori is found to be \(v_* = 40 n_H^{-1/2} \text{km s}^{-1}\).

By comparing the Galactic space-velocity components of the peculiar velocity of the star (based on the orientation of the bow shock cone) and that of the apparent motion of the star (based on the astrometric solutions), we derived the space-velocity components of the ISM flow around the star. Assuming that the ISM flow in the vicinity of \(\alpha\) Ori emanates from the Orion OB 1 association, we find the particle number density per hydrogen nucleus \((n_H)\) in the ISM around \(\alpha\) Ori to be 1.5 to 1.9 cm\(^{-3}\), which translates to a 11 km s\(^{-1}\) flow.

Owing to higher spatial resolution of the data, we may be witnessing the development of a vortex ring along the surface of the bow due to instabilities. This research demonstrates that far-IR images of stellar wind bow shocks are excellent diagnostic tools to investigate the kinematics of the bow and the characteristics of the ISM in the vicinity of the star. These stellar wind bow shocks have been found not only around M supergiants but also around OB stars (Van Buren & McCray 1988) and an AGB star (Ueta et al. 2006). Therefore, this avenue of research is going to flourish with the coming of the AKARI All-Sky Survey (Murakami et al. 2007) followed by new opportunities with Herschel Space Telescope and Stratospheric Observatory for Infrared Astronomy, because there will be a wealth of new far-IR data on the stellar wind bow shocks around variety of mass-losing stars.

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Fig. 1. AKARI/FIS false-color maps of α Ori in the SW bands - N60 (65µm) and WIDE-S (90µm) at 15'' pixel$^{-1}$ scale - and in the LW bands - WIDE-L (140µm) and N160 (160µm) at 30'' pixel$^{-1}$ scale - from left to right, respectively. Background emission has been subtracted by a combination of temporal filters during data reduction. RA and DEC offsets (with respect to the stellar peak) are given in arcminutes. The wedges at the top indicate the log scale of surface brightness in MJy sr$^{-1}$. North is up, and east to the left.
Fig. 2. Close-up of the northern arc structure in the WIDE-S (90\,\mu m) map. RA and DEC offsets (with respect to the stellar peak) are given in arcminutes. The wedges at the top indicate the log scale of surface brightness in MJy sr$^{-1}$. North is up, and east to the left. The white line is the Wilkin (1996) curve that delineates the analytic solution at the 55$^\circ$ position angle at the 47$^\circ$ inclination angle. The black star and triangle indicate the position of $\alpha$ Ori and of the apex of the best-fit bow shock cone projected in the plane of the sky, respectively.