Milky Way Rotation from Cepheids

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More than one thousand radial velocity measurements of Milky Way classical Cepheids have been gathered since 1983 with the spectrometer CORAVEL[1] installed at the Danish 1.5-m telescope at La Silla. As they are bright, young disk population stars, with accurately known distances (via period-luminosity or period-luminosity-colour relations), and as their late spectral type facilitates radial velocity determinations, cepheids can be used as powerful indicators of the motion of the disk of our Galaxy. Indeed, 450 radial velocity measurements of faint cepheids were realized at La Silla specifically with the aim of studying the rotation of the Galaxy, in particular of obtaining accurate values for the Oort constant A, the curvature of the rotation curve and the distance to the galactic centre $R_{\odot}$. Recent developments in galactic dynamics, and N-body simulation techniques, may now permit some other finer characteristics of the local velocity field to be examined (Pont et al., 1994a, b).

As a follow-up of this programme, we began last winter measuring radial velocities of very faint galactic cepheids towards the outer parts of the Galaxy. These objects, inaccessible to CORAVEL, were observed with ELODIE[2], a fibre-fed echelle spectrograph installed at the 1.93-m telescope of the Haute-Provence Observatory, France. The radial velocities were computed from low signal-to-noise spectra using a cross-correlation technique, increasing the magnitude limit up to the 15th.

1. Centre-of-Mass Velocities

The measured radial velocity of a cepheid does not only reflect its movement in the Galaxy, but is a combination of this and the motion of its pulsating photosphere. Thus, a good phase coverage of the pulsation cycle is needed before the centre-of-mass velocity (or "Ŏ") can be evaluated.

Our strategy has been – in order to minimize the observation time – to get five measurements for each target cepheid evenly spread at 0.2 phase intervals. Five measurements proved sufficient to determine a cepheid Ŏ with an uncertainty of 2–3 km s^{-1}, small enough to be unimportant compared to the 9–11 km s^{-1}, intrinsic velocity dispersion of young stars such as the cepheids. The Ŏ was evaluated by fitting either the light curve of the cepheid itself or the velocity curve of another cepheid of similar period to the five data points. The fitted curve can be written:

$$C(t) = v_o + A \times (\text{light or typical velocity curve } (t - t_o))$$

where the three free parameters v_o, A and t_o are the Ŏ, the amplitude ratio and a zero-point phase shift (see Fig. 1).

The first method is justified by the fact that for extensively measured cepheids the light curve is observationally found to resemble the radial velocity curve. The second, from the fact that cepheids of similar periods tend to have similar velocity curves (the curve shape follows the "Hertzsprung sequence").

Only 450 measurements were sufficient to obtain a good estimate of the Ŏ for 87 cepheids.

2. Galactic Rotation

The 87 new Ŏ determinations were added to the existing sample of cepheids with known radial velocities, forming an extended sample of 278 galactic classical cepheids with reliable radial velocity and photometry. We then calculated distances for these objects through a Period-Luminosity-Colour relation due to Feast & Walker (1987). The position of the cepheids in the galactic disk as given by this relation is displayed in Figure 2, the cepheids measured with CORAVEL are drawn as black squares.

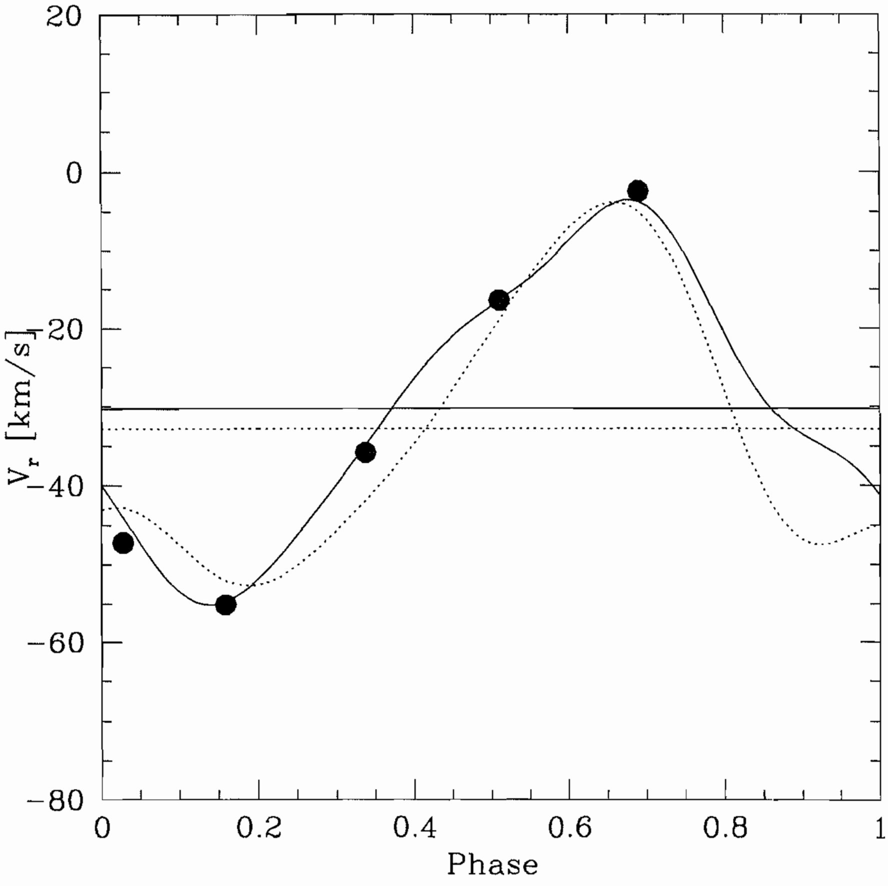

Figure 1: *An example of our method of calculating the centre-of-mass velocity of a cepheid from 5 measurements with a good phase coverage. The five points are the measured radial velocities, subject to a 1–3 km s^{-1} error, the continuous lines show the actual velocity curve and mean velocity, and the dashed lines show the fitted curve – the radial velocity curve of another cepheid with a similar period – and the recovered mean velocity. Even in this rather unfavourable case of an 11-day-period star (a period for which velocity curves are markedly heterogeneous) and with a slightly uneven phase coverage, the mean velocity is recovered within 3 km s^{-1}.*

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[1] For a description of CORAVEL, Baranne et al. (1979).

[2] A short presentation of ELODIE is given in "La lettre de l'OHP", 1993, No. 11.

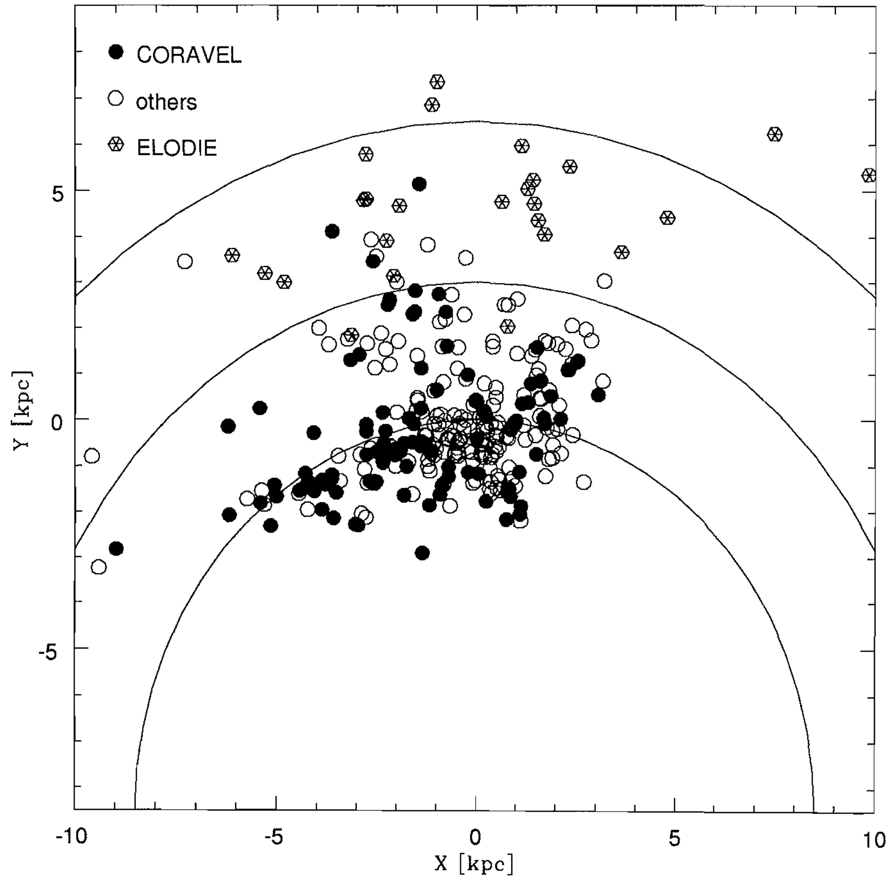

Figure 2: *Position of the classical cepheids projected on the galactic plane. Coordinates are in kpc from the Sun. The galactic centre is at (0, −8.5). Circles at $R = R_\odot$, $R = 11.5$ kpc and $R = 15$ kpc are shown. Black symbols indicate cepheids measured with CORAVEL, white symbols other cepheids with known radial velocity. Hexagons indicate the approximate position of the faint cepheid measured with ELODIE, if they are classical cepheids. Some of them, especially in the northern part (right), may be type II cepheids, and in that case their distance is overestimated.*

The sample covers an extension of about 70° as seen from the galactic centre, and a range of galactocentric distances from 6.5 kpc to 11.5 kpc (with $R_\odot$ = 8.5 kpc). The large size of this domain permits a firm determination of $R_\odot$ and A, and a consideration of higher-order terms expressing the shape of the rotation curve near $R = R_\odot$.

An axisymmetric rotation model applied to these data yields the following:

$R_\odot = 8.09 \pm 0.30$ kpc
distance to the galactic centre
$A = 15.92 \pm 0.34$ km s^{-1} kpc^{-1}
Oort constant A
$u_o = 9.32 \pm 0.80$ km s^{-1}
velocity of the sun relative to the LSR
$v_o = 11.18 \pm 0.65$ km s^{-1}
along the U and V axes

Two additional parameters, A2 and A3, the second and third derivative of the rotation curve at $R_\odot$, were also included in the fit. The corresponding rotation curve is shown in Figure 3 as a dashed line, along with rotation velocity determinations from CO measurements and H II regions (Clemens 1985, Blitz et al. 1982). The $R_\odot$ given by this analysis is slightly lower than the value currently recommended by the IAU, 8.5 kpc. The value of A is, whether or not A2 and A3 are used in the fits, higher than that of previous cepheid studies, indicating a steeper decrease of the rotation curve near $R = R_\odot$. We considered the effect of a modification in the cepheid distance scale (it is now considered unlikely that the cepheid scale zero-point is in error of more than 0.1–0.15 magnitudes). A zero-point change of plus or minus 0.15 mag brings the (A, $R_\odot$) pair to (7.6, 17.1) and (8.7, 14.8) respectively. The value 2A $R_\odot$ is almost insensitive to a zero-point shift and remains near 260 km s^{-1}.

3. The Residual Velocity Field

The velocity residual of a star is defined as the difference between its observed radial velocity and the radial velocity expected from the axisymmetric rotation model.

The k-term problem

An immediate problem arises with these residuals, already recognized by Stibbs in 1956: their mean should be zero, but is observationally nearer to −3 km s^{-1}. We get $\langle v_{obs} - v_{mod} \rangle = -2.33$ km s^{-1}. This residual velocity shift has been dubbed "k-term".

Explanations for this k-term have proceeded along two main lines: it could either be an artifact of the way the γ-velocities were calculated caused by the fact that the layers responsible for a cepheid's spectral lines changed during the pulsation – and therefore that the zero-point of the velocity curve was shifted relative to the true centre-of-mass velocity – or be a real dynamical effect reflecting a deviation from the axisymmetric rotation model.

Both explanations run into difficulties: a 3 km s^{-1} intrinsic k-term is difficult to explain with the current pulsation models for cepheids and the residuals do not correlate with period, colour or light curve amplitude, as may be expected in such a case, whereas a dynamical k-term seems suspect, since the residuals do not correlate with distance, as expected in a uniform contraction or expansion. That last fact seems to imply that the sun is in a somewhat special position relative to the residual velocity field, a rather unfashionable assumption.

The first explanation is usually favoured, and a constant shift added to the velocities in the galactic rotation analysis for cepheids.

But CORAVEL measurements for cepheids belonging to five open clusters, compared with CORAVEL radial velocities for other members of these clusters (Mermilliod et al. 1987), allowed us to reconsider the problem. The cepheids in these clusters are seen to match very closely the velocity of the other member stars. This is a strong argument against an intrinsic k-term, and makes the explanation by non-axisymmetric motions all the more plausible.

A comparison with selected fields of an N-body simulation for the galaxy, realized by R. Fux (1994), shows that k-terms of a magnitude up to 5 km s^{-1} are typical when an axisymmetric rotation model is applied to a galaxy left to evolve for a few billion years and to form a bar from an initially axisymmetrical state.

Thus, we feel confident in saying that the k-term can be attributed to real dynamical effects – non axisymmetrical motions – and that the Ŏ recovered from cepheid spectra does represent the centre-of-mass radial velocity.

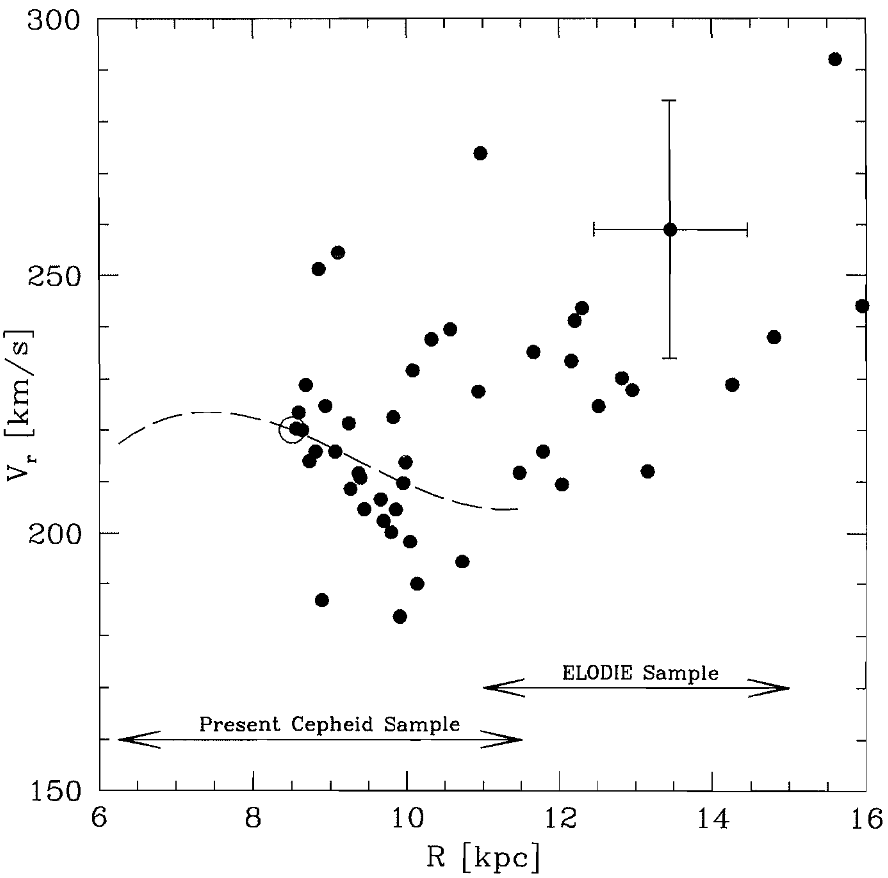

Figure 3: *The circular rotation velocity as a function of the galactocentric radius R for R=6–16 kpc.*

The dashed line shows the rotation curve obtained from the cepheid sample measured with CORAVEL, if we adopt θ_o = 220 km s^{-1}.

The white circle marks the pair ($R_\odot$, $\theta_\odot$).

The black points are rotation velocity determinations from CO and H II regions data, in Clemens 1985. Typical error bars are shown for one point in the upper right.

Note that the uncertainties of the gas distances are not uncorrelated, and that a distance error moves a point diagonally from the upper right to the lower left (since the distance enters the calculation of both R and v_{rot}). Thus a systematic error in the distance scale would appear as a global increase or decrease of v_{rot}.

The range in R covered by the former cepheid sample and by the new ELODIE sample are shown at the bottom. Hopefully, this new sample could allow us to determine whether the rotation velocity decrease for 8 < R < 10 kpc in the cepheids reflects a local motion of some type, or if it really shows a falling rotation curve for $R > R_\odot$.

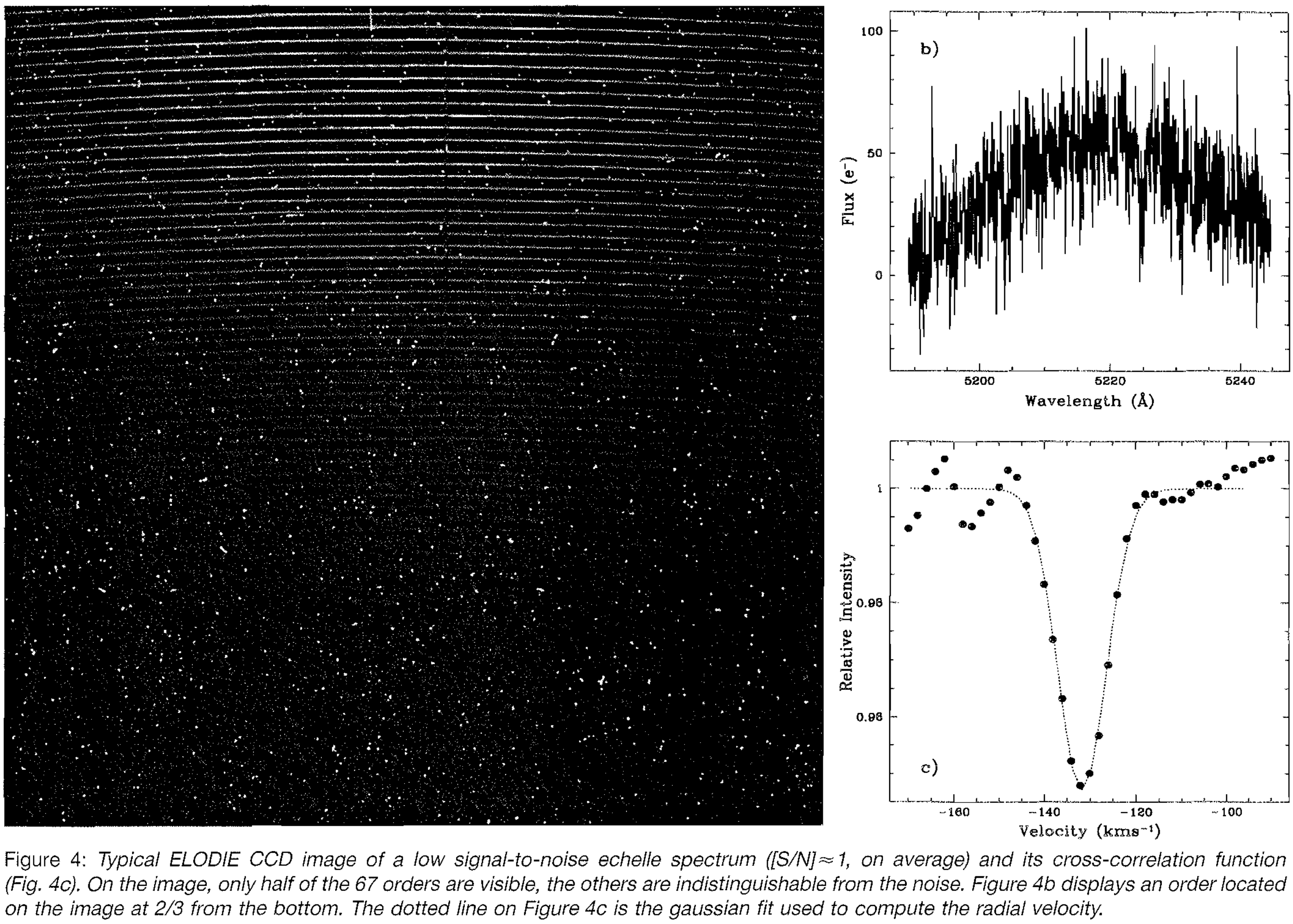

Figure 4: *Typical ELODIE CCD image of a low signal-to-noise echelle spectrum ([S/N]≈1, on average) and its cross-correlation function (Fig. 4c). On the image, only half of the 67 orders are visible, the others are indistinguishable from the noise. Figure 4b displays an order located on the image at 2/3 from the bottom. The dotted line on Figure 4c is the gaussian fit used to compute the radial velocity.*

4. Towards the Galactic Rotation Curve Beyond 12 kpc with ELODIE

A good knowledge of the outer rotation curve is interesting since it reflects the mass distribution of the Galaxy, and since it permits the kinematic distance determination of young disk objects. The rotation curve between 12 and 16 kpc is not clearly defined by the observations as can be seen on Figure 3. Both the gas data and the cepheid data clearly indicate a rotation velocity decrease from $R_\odot$ to $R = 12$ kpc, but then the gas data outline a flat or rising curve at $v_{rot} \simeq 230$ km s^{-1} for $R > 12$ kpc. The present cepheid sample suffers an effective cutoff in radial velocity measurements around $V = 12.5$ mag, so that the range in galactocentric distances that it covers is limited to the one indicated in the figure.

ELODIE is a high-resolution (45,000) fibre-fed spectrograph with a fixed wavelength range from 3900 to 6800 Å. It was built by collaboration between the Haute-Provence Observatory, the Marseilles Observatory and the Geneva Observatory and is now permanently installed at the 1.93-m telescope of the Haute-Provence Observatory. This instrument possesses an automatic reduction programme called INTER-TACOS running on a SUN SPARC station to achieve on-line data reductions and cross-correlations in order to get the radial velocity of the target stars minutes after the observation. The cross-correlation algorithm used to find the radial velocity of stars mimics the CORAVEL process, using a numerical mask instead of a physical one (for any details, see Dubath et al. 1992). This technique allows us to extract easily the radial velocity of cool stars (later than F0) from spectra having a signal-to-noise ratio of about one and thus to get the velocity of Cepheids of 15th magnitude with an exposure time of about one hour or so (see Fig. 4).

We initiated last winter a programme of about 25 cepheids to cover the 11–15 kpc range of galactocentric distances. The approximate positions of the target cepheids are indicated as crossed hexagons on Figure 2. The analysis of this sample should constrain the rotation curve from 12 kpc to 15 kpc and answer the question:

"Does the dip of the rotation curve at 11 kpc exist and does the rotation curve determined from cepheids follow the gas rotation curve?"

The answer will give an important clue about the reality of a local non-axisymmetric motions and will permit to investigate a possible systematic error in the gas or cepheids distance scale (due for instance to metal deficiency).

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Interstellar Na I Absorption Towards Stars in the Region of the IRAS Vela Shell

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Introduction

The Hα emission associated with the Gum Nebula is confined to a circular region which has a diameter of approximately 36° (Chanot and Sivan, 1983). In the southern brighter part of the nebula, near γ^2 Velorum, the emission measure is higher by a factor of ~3 as compared to the fainter, outer regions. We examined the IRAS SuperSky Flux maps in the entire Gum Nebula region and discovered a ring-like structure (Fig. 1) coincident with the bright southern part, which we have termed the IRAS Vela Shell (Srinivasan Sahu, 1992; Srinivasan Sahu and Blaauw, 1994). This structure, centred around the Vela OB2 group of stars (the B-association of which γ^2Velorum is a member, which we will refer to as Vela OB2, according to the nomenclature of Ruprecht et al., 1981), has an average radius of ~8°. The section of the IRAS Vela Shell at positive galactic latitudes is not clearly seen due to confusion with the background galactic emission. The half circle of dark clouds at negative latitudes coincident with the IRAS Vela Shell is apparent in the maps by Feitzinger and Stüwe (1986), in their study of the projected dark cloud distribution of the Milky Way. The IRAS maps clearly show that the cometary globules and dark clouds in the Puppis-Vela region, catalogued from the ESO-SERC IIIaJ plates (for example, Hawarden and Brand, 1976), are part of this ring-like structure.

The members (known and probable) of Vela OB2 lie within the IRAS Vela Shell which in fact just envelops the stars in this association. The Vela OB2 stars are therefore physically associated with the IRAS Vela Shell. Based on distance estimates to γ^2 Velorum and Vela OB2, the distance to the centre of this ring-like structure is ~450 pc and its estimated mass is ~10^6 $M_\odot$. Both from the morphology on IRAS maps as well as from a study of the kinematics of the ionized gas in Puppis-Vela (Srinivasan Sahu and Sahu, 1993) the IRAS Vela Shell and the Gum Nebula appear to be two separate structures which just happen to overlap in projection.

We have analysed proper motions of the early-type stars in the region and there is strong evidence that the Vela OB2 stars are indeed part of a B-association. The association nature is further confirmed by the fact that both from position in the galactic (l, b) diagrams and its distance, Vela OB2 appears to form an extension of the string of association subgroups known as the Sco-Cen association and thereby a part of the Gould belt. Strömgren photometry by Eggen (1982) and an analysis by us using data from the homogeneous