Mem. S.A.It. Suppl. Vol. 18, 91

Memorie della
Supplementi

Estimation of pattern speed in external galaxies using very young, stellar clusters*

P. Grosbøl[1] and H. Dottori[2]

[1] European Southern Observatory, Garching bei München, Germany
e-mail: pgrosbol@eso.org
[2] Instituto de Física, Universidad Federal do Rio Grande do Sul, Porto Alegre, RS, Brazil

Abstract. In the 60's, Prof. Strömgren proposed to use space velocities and ages of moderately young stars to compute their places of formation in order to study the spiral structure in the Galaxy. We have extended this idea to very young stellar clusters in nearby disk galaxies. Near-infrared (NIR) K-band images of grand-design spiral galaxies often show bright knots along their spiral arms. Such knots in NGC 2997 have been identified as massive stellar clusters with ages of less than 10 Myr using JHK photometry and K-band spectra. Ages of these clusters can be estimated from JHK photometry. Their azimuthal distances from the spiral arms, as measured in the K-band, correlates with their ages suggesting that the pattern speed of an underlying density wave can be derived. This method is tested on the grand-design spiral NGC 2997 using VLT data.

Key words. galaxies: individual: NGC 2997 – galaxies: spiral – galaxies: star clusters – galaxies: structure – infrared: galaxies – techniques: photometry

1. Introduction

Strömgren (1963) suggested to use the migration of young stars with known ages and space velocities to estimate the pattern speed of a density wave in our Galaxy (Lin & Shu 1964; Yuan 1969). In external galaxies where individual stars cannot be observed, one may consider to use integrated properties of blue, young objects (such as HII regions and OB associations) which often are concentrated in the arms of grand-design spiral galaxies. Strong and very varying attenuation by dust in the arm regions make it difficult to determine reliable, intrinsic colors of such very young objects in visual bands. In the NIR, several spiral galaxies had bright knots along their spiral arms (Grosbøl & Patsis 1998). Such knots in NGC 2997 were identified as very young stellar cluster (ages <10 Myr) using K-band spectra obtained with ISAAC/VLT (Grosbøl et al. 2006).

It is possible to estimate accurate ages for clusters younger than <8 Myr from their integrated NIR colors and/or Brγ emission due to the rapid evolution of their high mass stars and the low attenuation by dust. Although space velocities for the clusters cannot be obtained, the general rotation curve of the host galaxy provide enough information to make a crude

Send offprint requests to: Preben Grosbøl
* Based on observations collected at the European Southern Observatory, Chile (ESO programme 278.B-5042)

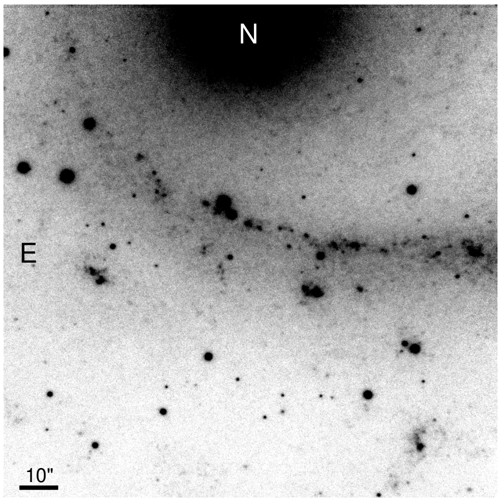

Fig. 1. Direct K-band image of the field around the southern arm of NGC 2997 used for the analysis. The scale is indicated by the bar in the lower left corner.

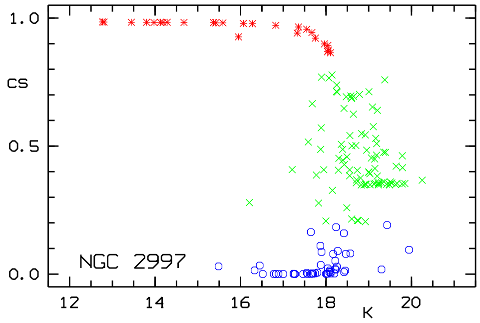

Fig. 2. The class_star classifier, cs, as a function of apparent K-band magnitude for all sources detected by SExtractor in the NGC 2997 field. Different source groups are indicated by symbols: diffuse (open circles), compact (crosses), and star-like (asterisks).

estimate of their birthplaces assuming that they follow roughly circular orbits.

A further advantage of using NIR observations is that phase and shape of a density wave can be measured directly. This opens the way for estimating its pattern speed by comparing ages of individual clusters with their azimuthal offset relative to the spiral perturbation. In addition, one may study star formation induced by such density variations e.g., through large-scale shocks or compressions in the gas (Roberts 1969). In the current paper, we study the spatial and color distributions of young stellar clusters in the southern arm of NGC 2997 in order to test the feasibility of this scheme to estimate the pattern speed in external galaxies.

2. Data and reductions

Deep JHK-Brγ images of a field around the southern arm of NGC 2997 (see Fig. 1) were obtained with ISAAC/VLT in order to study the properties of stellar clusters. The K-band map reached a limiting magnitude of K = 19 mag (with errors of ±0.1 mag) corresponding to M_K = –11.3 mag (assuming a distance of 11.6 Mpc) while the linear resolution was 45 pc with a seeing of $0\farcs8$ measured on the final stacked images. Besides the broad-band colors, a Brγ index (Brγ–K) was estimated with a zero point defined by the average value for foreground stars in the field.

Sources were identified on the K-band image using SExtractor (Bertin & Arnouts 1996) after which aperture magnitudes (diameter of 2″) were measured at these source locations for all filters. The SExtractor class_star classifier (cs), which range from 0 for diffuse sources to 1 for point-like targets, is shown in Fig. 2. Sources were divided into 3 groups: diffuse (cs<0.3), compact (0.3<cs<0.8), and star-like (0.8<cs). The diffuse sources are well separated from the compact ones and on average brighter.

3. Spatial and color distributions

The spatial locations of the sources are shown in Fig. 3 for the NGC 2997 field (see Fig. 1). The average position of the southern spiral arm (with a pitch angle of $-22\overset{\circ}{.}6$) is indicated by a dashed line which outline the phase of the m = 2 Fourier component of the azimuthal K-band intensity variation as a function of radius. It is clear that only the diffuse sources (open circles) concentrate along the spiral on its inner side while the other types of objects have a more uniform distribution.

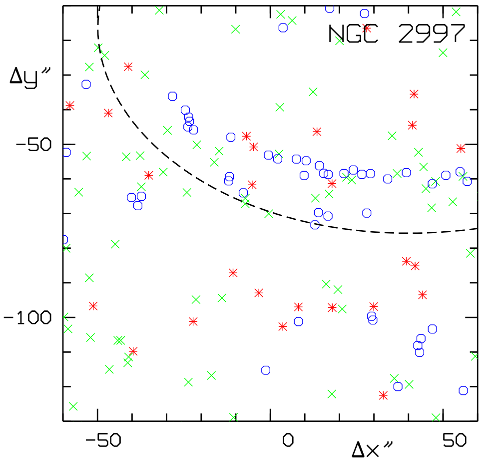

Fig. 3. All objects detected on the K-band image of the NGC 2997 field. The dashed line indicates the average location of the two-armed spiral pattern. For symbols see Fig. 2.

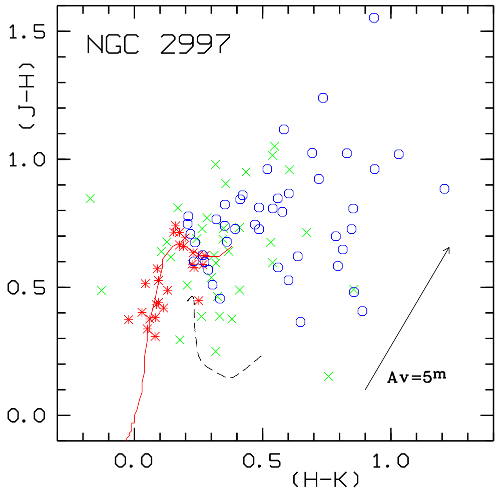

Fig. 4. Color-color diagram for all sources with color errors <0.1 mag in the NGC 2997 field. The full drawn line indicates the stellar main sequence while the dashed line shows a standard Starburst99 evolutionary track for stellar clusters with continuous star formation for ages up to 50 Myr. The galactic reddening vector is indicated for $A_V = 5$ mag. Symbols are the same as in Fig. 2.

The $(H-K)-(J-H)$ diagram for the sources is given in Fig. 4 where the arrow indicates the standard galactic reddening vector. Galactic foreground stars are located along the stellar main sequence as outlined by the full drawn line. An evolutionary track for stellar clusters with continuous star formation was computed using Starburst99 (Leitherer et al. 1999) and plotted with a dashed curve. The model had a Salpeter IMF, an upper mass of 120 $M_{\odot}$, and solar metallicity. The track starts around $(H-K) = 0.5$ mag after which $(H-K)$ becomes bluer until around 7 Myr when $(J-H)$ gets redder. The colors do not change much after 15-20 Myr when they approach those of globular clusters at (0.2, 0.7). Models with instantaneous star formation are somewhat bluer and reach slightly higher $(J-H)$ values. The non-stellar sources are scattered above the track suggesting typical absorptions by dust of the order of $A_V = 5$ mag but with a large spread. The complex geometry of stars and dust in these regions make it possible that the inner parts of the clusters have much higher attenuation than indicated by the average value. The red diffuse sources have colors compatible with ages <10 Myr. The compact sources are on average 2 mag fainter and have larger errors in their color indices.

A reddening *free* color index $Q = (H-K) - 0.59 \times (J-H)$ may be computed assuming a standard galactic reddening law and a screen model. Starburst99 models suggest that zero-age clusters have Q values around 0.4 mag and then decreases to –0.1 mag at 10 Myr after which the index remains almost constant. A few sources have lower Q values which may suggest that either the reddening law differs slightly or the screen model is inappropriate due to the complex star-dust geometry (Witt et al. 1992; Pierini et al. 2004). There is an anti-correlation between Q and Brγ indices for diffuse sources as expected from Starburst99 models. Due to the smaller S/N ratio for Brγ, the Q index was preferred as an age indicator.

4. Locations relative to spiral arms

The distribution of diffuse and compact sources relative to the spiral arms is displayed in Fig. 5 using the azimuthal distance $\Delta\theta$ from

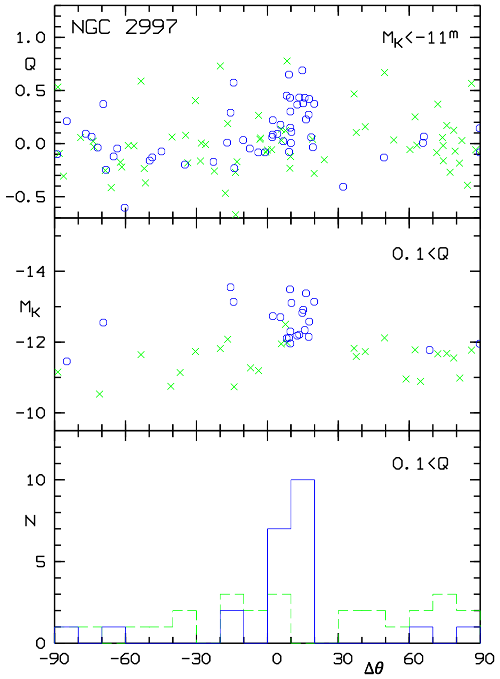

Fig. 5. Distribution of non-stellar sources as a function of their azimuthal distance $\Delta\theta$ from the two-armed spiral intensity maximum. The top panel shows Q for sources with M_K<–11 mag, the middle panel displays M_K for young sources with Q > 0.1 mag, while the button panel gives the histogram of young sources. The same symbols as in Fig. 2 are used.

the mean two-armed spiral as derived from a Fourier analysis of a *K*-band map (Grosbøl et al. 2004). The diffuse sources are strongly concentrated in a region 0°-20° inside the intensity maximum of the spiral arm while the compact objects have a more uniform distribution. The sharpness of the peak of young, diffuse objects (open circles) and its offset with respect to the spiral arm intensity maximum (i.e., $\Delta\theta$=0°) indicate a strong star formation activity just inside the spiral arms possibly associated to non-linear compression of gas in a spiral potential (Roberts 1969; Gittins & Clarke 2004).

The concentration in the arm region is also seen clearly in the plot of absolute magnitudes M_K for young clusters with 0.1 mag < Q as a function of their azimuthal offset $\Delta\theta$ where a sharp transition occurs around M_K = –12 mag. The transition could be associated to the expulsion of gas and dust from the clusters when the first supernovae explode (Bastian & Goodwin 2006; Goodwin & Bastian 2006). This would make the clusters appear more compact, disrupt star formation and therefore lead to a more rapid fainting of them. It is noted that only young diffuse objects (i.e., 0.1 mag < Q) are located in a narrow region just inside the spiral arm whereas the compact sources have a uniform distribution. This suggests that formation of the most massive clusters requires a triggering by a compression of gas associated to the spiral arm while less massive clusters are formed more randomly over the galactic disk.

The top diagram of Fig. 5 displays the relation between azimuthal offset and Q index (age for 0.1 mag < Q) for the non-stellar sources. Compact sources (crosses) and those with Q < 0.1 mag, for which Q cannot be used as an age indicator, are distributed uniformly. On the other hand, the distribution of very young diffuse sources (open circles) suggests a correlation where the youngest objects are further away (inside) from the spiral arm defined by the *K*-band intensity variation. A rough estimate of the gradient indicates that a 10° change in $\Delta\theta$ corresponds to a variation in Q of 0.2–0.3 mag with a visual best fit of 0.22 mag/10°. The scatter may be caused by several factors such as photometric errors, and formation of clusters in a region with finite azimuthal width. Further, clusters over a significant radial range have been used (to improve statistics) which smears out the relation due to the slightly different pitch angles of the spiral potential and the associated star forming front as outlined by the dust lanes (Grosbøl et al. 1999).

5. Birthplaces and pattern speed

Birthplaces of the youngest clusters can be estimated using the rotation curve which is almost flat at 185 km s^{-1} at the radii of the clusters (Peterson 1978). This corresponds to a motion of 190 pc or 3.″9 per Myr. Assuming that all clusters are formed in a star forming front with the same shape as the density wave (just offset from it), a first order estimate of the pattern speed can be given as:

$$\Omega_{\rm p} = (V_c - V_r/\tan(i))/r - \delta\theta/\delta a$$

where V_c is the circular velocity, V_r the radial velocity, r the average radius of the clusters, i the pitch angle of the spiral (negative for trailing patterns), and $\delta\theta$ the change in azimuthal offset $\Delta\theta$ for clusters with an age difference of δa. This approximation is valid only for $\delta a \ll \pi/2\kappa \approx 50$ Myr for NGC 2997 where κ is the epicyclic frequency.

The estimate of $\delta\theta/\delta a$ can be derived from the top diagram in Fig. 5 which suggests $\delta\theta/\delta Q = 0.22\,\mathrm{mag}/10°$. The Starburst99 model indicates a $\delta a/\delta Q$ of –22 Myr per mag for the range of Q around 0.2 mag with a slightly more shallow slope for models with upper mass limits below 30 $M_\odot$. This yields $\delta\theta/\delta a \approx 36$ $\mathrm{km\,s^{-1}\,kpc^{-1}}$ and $\Omega_{\rm p} = (54 - 36)\ \mathrm{km\,s^{-1}\,kpc^{-1}}$ = 18 $\mathrm{km\,s^{-1}\,kpc^{-1}}$ for pure circular velocities while $V_r = -10\ \mathrm{km\,s^{-1}}$ would lower the estimate to around 12 $\mathrm{km\,s^{-1}\,kpc^{-1}}$. Both estimates of the pattern speed place the inner Lindblad resonance (ILR) close to the inner radius of the main spiral pattern and co-rotation significantly outside the symmetric pattern in good agreement with other determinations.

6. Conclusions

The analysis of sources in a field centered on the southern arm of NGC 2997 observed in NIR bands with ISAAC/VLT offers the following tentative conclusions:

- the youngest stellar clusters with magnitudes $M_K < -12$ mag are concentrated in the arm regions,
- the bright, young clusters (0.1 mag $< Q$) show an age gradient where the youngest are further away (in front of) the spiral arm,
- the pattern speed of the density wave can be estimated to $\approx$18 $\mathrm{km\,s^{-1}\,kpc^{-1}}$ using this gradient and assuming circular motions and formation along a front with the same shape as the spiral arms, and
- fainter young clusters have a more uniform distribution.

This is consistent with the standard density wave picture where the main spiral pattern starts just outside the ILR. The most massive clusters seem to be triggered by a front associated to the density wave while smaller clusters are more uniform distributed. The use of broad band NIR photometry to estimate ages of very young stellar clusters in spiral galaxies and from those calculate birthplaces provides a new independent method to estimate the pattern speed of density waves in nearby, grand-design spirals.

References

Bastian, N., & Goodwin, S. P. 2006, MNRAS, 369, L9

Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393

Gittins, D. M., & Clarke, C. J. 2004, MNRAS, 349, 909

Goodwin, S. P., & Bastian, N. 2006, MNRAS, 373, 752

Grosbøl, P., & Patsis, P. A. 1998, A&A, 336, 840

Grosbøl, P. J., Block, D. L., & Patsis, P. A. 1999, Ap&SS, 269, 423

Grosbøl, P., Patsis, P. A., & Pompei, E. 2004, A&A, 423, 849

Grosbøl, P., Dottori, H., & Gredel, R. 2006, A&A, 453, L25

Leitherer, C., Schaerer, D., Goldader, J. D., et al. 1999, ApJS, 123, 3

Lin, C. C., & Shu, F. H. 1964, ApJ, 140, 646

Peterson, C. J. 1978, ApJ, 226, 75

Pierini, D., Gordon, K. D., Witt, A. N., & Madsen, G. J. 2004, ApJ, 617, 1022

Roberts, W. W. 1969, ApJ, 158, 123

Strömgren, B. 1963, QJRAS, 4, 8

Witt, A. N., Thronson, H. A., & Capuano, Jr., J. M. 1992, ApJ, 393, 611

Yuan, C. 1969, ApJ, 158, 871