Are Bulges of Disk Galaxies Triaxial?

Evidences from the Photometry and the Gas Dynamics

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Introduction

It is now generally accepted that elliptical galaxies are triaxial in shape. There are at least two strong observational hints that this is indeed the case: the first one is the well-known fact that elliptical galaxies are, normally, slow rotators (Bertola 1972; Bertola and Capaccioli 1975; Illingworth 1977) whose shape is not due to rotation and therefore must be due to the flattening of their velocity dispersion ellipsoids. This makes it likely that the dispersion velocity tensor is flattened also along the intermediate axis, so that the resulting galaxy's figure is triaxial, rather than oblate. Secondly, elliptical galaxies show radial variations in ellipticity and position angle of their apparent major axis (Bertola and Galletta 1979), a phenomenon that cannot occur if their shape is prolate or oblate. This observational evidence is supported by theory: we know now that several galaxy-formation scenarios (Aarseth and Binney 1978; see also Lake, and White 1987 for reviews) exist where collapse of the proto-cloud in its three main directions occurs on different timescales, making a triaxial object the most likely end-product of the scenario. Also, we know that triaxial stellar-dynamical models exist, which are stationary (except for perhaps a slow figure rotation), and stable to at least the grossest instabilities (Schwarzschild 1979).

However, although much circumstantial evidence exists in many different cases to indicate that a given elliptical galaxy is indeed triaxial, it is difficult to find a clear-cut example of an isolated galaxy which we are sure is triaxial. In fact, projection on the plane of the sky of a triaxial object involves four, a priori unknown, parameters: two viewing angles, θ and φ, and the two intrinsic axial ratios, b/a and c/a, while observations provide, as the only constraint, the apparent axial ratio ε. So, if we want to prove that a given elliptical galaxy is triaxial, recourse has to be made to more complicated, dynamical arguments; such is the case, for instance, of the galaxy studied by Davies and Birkinshaw (1986), and of NGC 5077, an elliptical with a gaseous disk, where these four parameters were determined in a straightforward way (Bertola, Bettoni, Danziger, Sadler and de Zeeuw, 1988, in preparation).

The situation for bulges of disk galaxies is, however, completely different: Lindblad (1956), arguing on the basis of purely geometrical arguments, proved that the bulge of M31 cannot be oblate, and it is now known (Stark 1977) that it is unlikely to be prolate also. The similarity of bulges of disk galaxies and ellipticals is now well-established, once objects of equal luminosity are compared. There seems to be, in fact, a continuum spectrum of properties which extends from giant elliptical galaxies down to small bulges (Davies 1987), the latest property to be studied being the existence of "normal" exponential disks in SOs and elliptical galaxies (Capaccioli and Vietri, 1988).

In the past, however, this continuum has been taken to imply that, since bulges seem to be oblate, so should be the small ellipticals. Here we argue the other way round: we show that a fair fraction of bulges (for which a deprojec-

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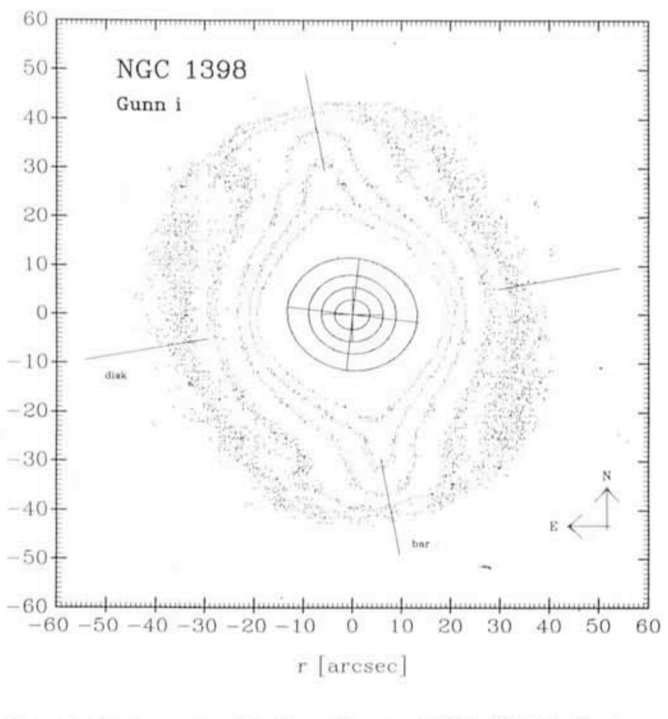

Figure 1: *Contour plot of the Gunn i frame of NGC 1398. On the inner four isophotes the fitted ellipses together with the respective major and minor axes are superimposed. The position angles of the bulge (PA = 89° and PA = 83°), bar (PA = 11°) and disk (PA = 100°) are indicated. The latter value was taken from Lauberts (1982).*

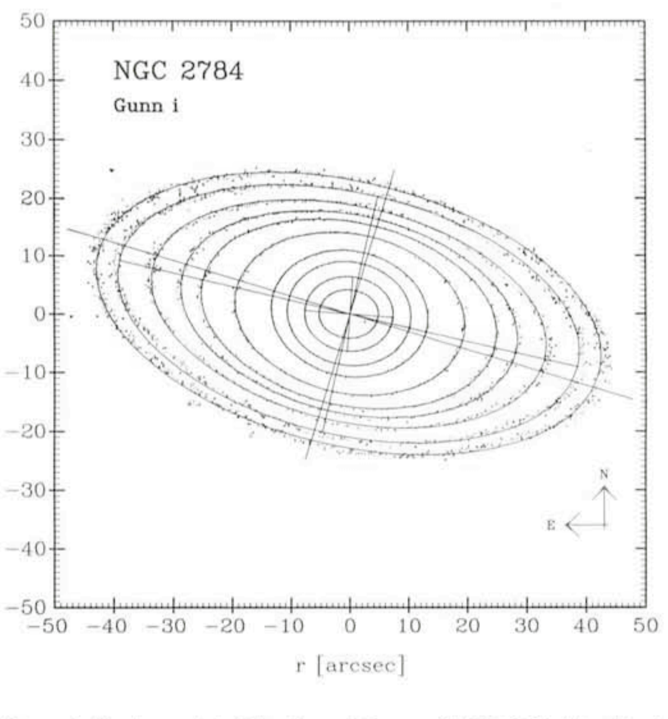

Figure 2: *Contour plot of the Gunn i frame of NGC 2784. The fitted ellipses are superimposed to the isophotes. In order to make the variation in position angle more evident, three major and minor axes at different radii are plottet, the last one representing the disk.*

tion is easier than for ellipticals) are triaxial, and we take this to imply that small ellipticals too are, most likely, triaxial. We stress here, furthermore, that our argument does not depend upon uncertain dynamical interferences, but exclusively on straightforward geometrical evidences. We will examine some dynamical evidence in the last section of this paper. In the next section we extend Lindblad's arguments to a large sample of spirals' bulges.

The Photometric Evidence

Lindblad's argument, in dealing with M31, was simple: he noticed that the apparent major axis of the bulge was misaligned with the apparent major axis of the disk by $\gamma = 12°$. He correctly reasoned that, if the bulge is oblate and its true minor axis coincides with the disk's axis of symmetry, one should have $\gamma = 0°$. He then deduced that the bulge could not be oblate but triaxial. This argument is not peculiar to M31, of course. So we decided to investigate photometrically a large number of spiral galaxies, hoping to find cases analogous to the Andromeda nebula.

In the period from December 31 to January 2, 1987 we obtained CCD pictures of 28 disk galaxies during an observing run at the ESO/MPI 2.2-m telescope equipped with the RCA CCD camera. We selected objects of various Hubble types ranging from S0 to late spiral type. For each galaxy at least two frames were obtained in the Gunn r and Gunn i filters in order to emphasize the older stellar population in the bulge region.

The frames were calibrated using standard techniques of normalized flat field division and bias correction. The galaxy images were analyzed using an ellipse fitting algorithm yielding the position angle PA of the galaxy's isophotal major axis and apparent ellipticity ε. The accuracy in determining these quantities is not limited by method since the formal errors would be of the order $\sigma(PA) \simeq \pm 1°$ and $\sigma(\varepsilon) \leq \pm 0.01$. The influence of the disk component's dust absorption on the isophotes poses much severer limits on the accuracy. Dust tends to mimic flatter isophotes which appear also to be twisted by several degrees. In order to minimize these effects we used therefore filters in the redder wavelength region where the light from the bulge is predominant. For the most part of the Galaxies observed we found in the bulge region no significant disturbance due to dust. For the remaining objects we applied appropriate masks on the affected regions and performed a reasonable interpolation of the isophotes. Because of the limited size of the CCD frames we used also position angle measurements of the disk's major axis from the sky survey prints.

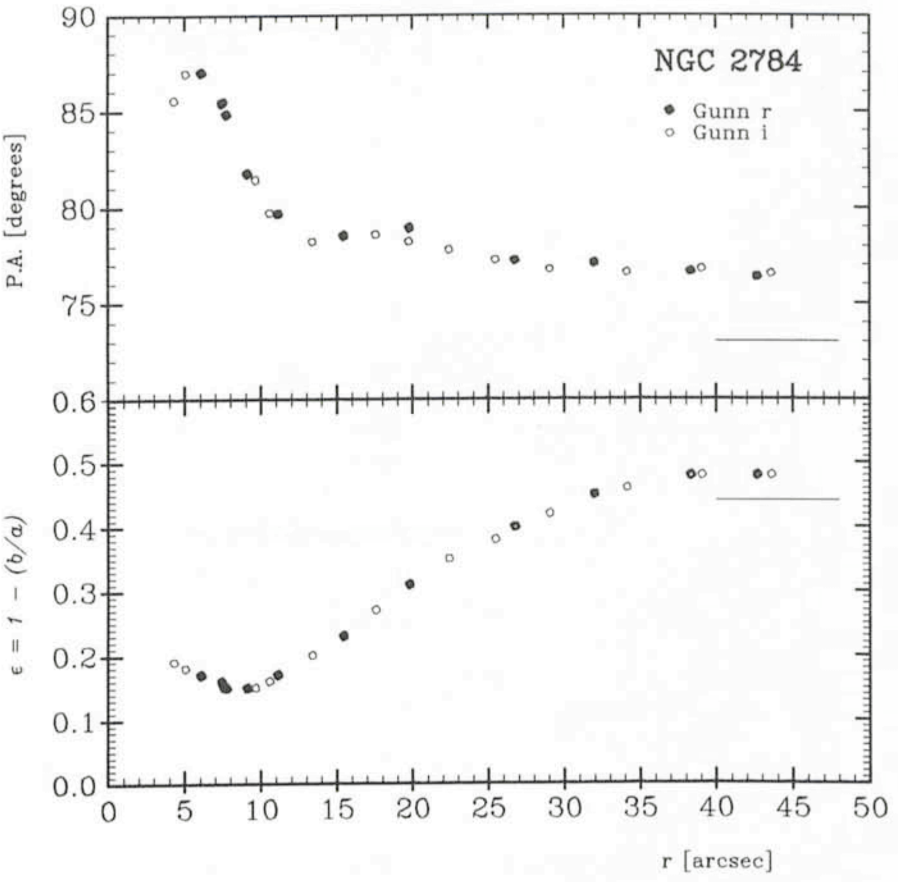

Figure 3: *Profiles of ellipticity and position angle as a function of radius for NGC 2784. The line indicates the respective values for the disk (Lauberts 1982).*

As a comparison, we included also a few barred galaxies in the programme, which do show the effect of a misaligned bulge with respect to the disk and the bar. One such case, NGC 1398 is shown in Figure 1. For this class of galaxies, the fact that the bulge is triaxial is well-known (Kormendy 1982); it has been ascribed to the dynamical interaction of the bulge with their prominent bars. As a further indication of the bulge's triaxiality an evident twisting of the isophotes ($\Delta PA \simeq 6°$) in the inner bulge region ($r < 13''$) was detected. Other non-barred examples have been mentioned in the literature, albeit never properly discussed (Boronson 1981; Gamaleldin and Issa 1983). Zaritsky and Lo (1986) concluded already, however based on a fairly small galaxy sample, that non-axisymmetric nuclear bulges should be generally anticipated.

In our survey, we have detected several possible cases of misaligned galaxies out of a total sample of 13 non-barred galaxies studied so far. The best case is represented by the S0 galaxy NGC 2784, which is very probably an almost dust-free system and whose isophotal twisting was also noticed by Gamaleldin and Issa. A contour plot of NGC 2784 is shown in Figure 2, together with the fitted ellipses. In order to make the variation in position angle more evident, three major and minor axes at different radii are superimposed. The outmost position angle indicated was taken from Lauberts (1982) since his measurements, based on sky survey prints, refer always to the disk region of the galaxy. The ellipticity and position angle profile is shown in Figure 3. The photometry in the Gunn i band yields exactly the same results, showing that we are not seeing any dust-related phenomenon. Figure 3, together with Figure 4, the ESO (B) Sky Survey print, show that the disk's major axis position angle is well-defined, and not due to the presence of spiral arms. Figures 2, 3 and 4 clearly show the existence of a misalignment by $\gamma = 14°$.

Could this misalignment have another cause? Once dust has been ruled out, the only remaining possibility is that the disk itself be flattened in its own plane (oval distortion). However, given the disk's apparent flattening of $\varepsilon \simeq 0.5$, one can show that the disk's true flattening in its own major plane needed to explain away $\gamma = 14°$, is $b/a \simeq 0.75$, a value that is probably inconsistent with the observations of most face-on disks. We be-

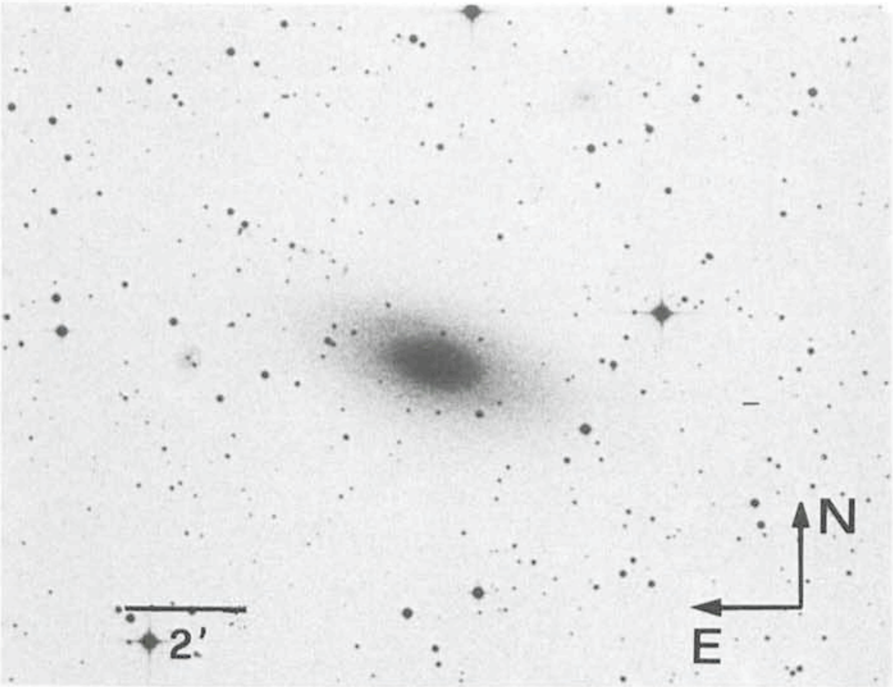

Figure 4: *NGC 2784. Reproduction from the ESO (B) Sky Survey print.*

lieve that this conclusively shows that *the bulge of NGC 2784 cannot be oblate.*

Could it be *prolate?* Stark (1977) has shown how this can be ascertained. If we again assume that disk and bulge have coincident minor axes (an assumption supported by observations of edge-on disk galaxies), then he showed that there are three constraints on the four free parameters of the projection: the disk's and bulge's apparent flattenings, and the angle γ. Basically, the disk's flattening gives us immediately one of the viewing angles, while the other two constraints are more complicated functions of all four unknown parameters. One can then find a one-parameter family of solutions for the projection equations, where the free parameter can be taken as the bulge's major axis position angle in the disk's plane, from the line of nodes. This exercise can be carried out for NGC 2784. The solution is shown in Figure 5. We see that all angles $\varphi > 142°$, lead to a c/a > b/a, which is an unlikely solution (when seen edge-on, such a bulge would look like a rugbyball with its major axis sticking out of the disk plane). Also, as expected, we see that a prolate solution is not very likely on statistical grounds, since it corresponds to a small range of position angles: only angles $142° > \varphi > 136°$ are consistent with this galaxy being roughly prolate, within the range of observational errors. Lastly, in this fortunate case, since the most likely distribution of values for φ is casual, i. e. flat, we see that *the most likely solution is a mildly triaxial bulge,* with axial ratios c/a $\simeq$ 0.4, and b/a $\simeq$ 0.6.

The Dynamical Evidence

Far from being unexciting, such mildly triaxial bulges may give rise to a deeply non rotationally-symmetric gas velocity field, as shown by Gerhard and Vietri (1986) in the case of the Milky Way, by Gerhard and Vietry (1987) in the case of an arbitrary bulge, and by Bertola, Gerhard, Rubin and Vietri (1988, work in progress) in the case of NGC 4845. The main effect that we expect, dynamically, from a flattened bulge, is that the gas orbits will be slightly elongated, with their longest axis pointing along the potential's intermediate axis. As a consequence, the gas velocity at the point closest to the galaxtic centre will be (considerably) higher than the velocity at the most distant point on the same orbit. Thus, depending on the viewing angle, the rotation curve may appear to have a hump (as in the case of the Milky Way, Gerhard and Vietri 1986), or may seem to be abnormally slowly rising. For bulges with de-Vaucouleurs-like luminosity profiles, velocity perturbations of over 100 km s^{-1} are expected. When observations of the whole velocity field are available, we can thus use the photometrically-determined parameters, plus the angle φ as fitting parameters of the whole field. In other words, by combining photometry and spectroscopy, we can find the angle φ and, thus, by looking at Figure 5, we can determine the intrinsic axial ratios of the bulge. It is exactly this exercise that has been carried out for NGC 4845, and, although in this case the photometric

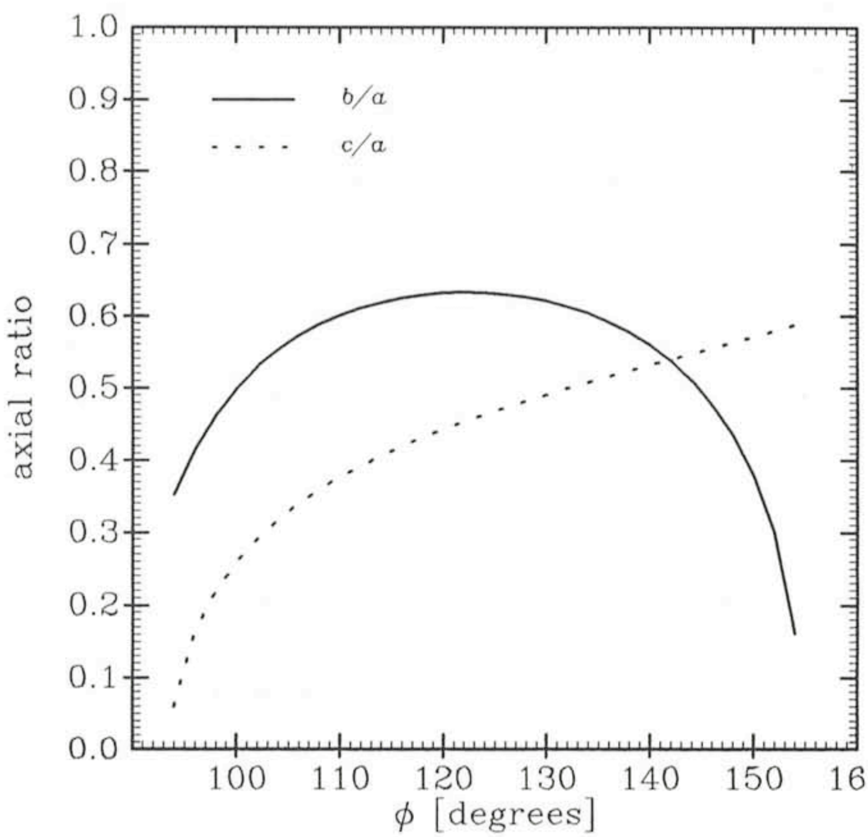

Figure 5: *Solution for the axial ratios b/a and c/a at different position angle φ with respect to the major axis for the bulge of NGC 2784 in the disk plane.*

observations are marred by a large amount of dust, making the determination of the galaxy's axial ratios somewhat unreliable, still these arguments have received considerable support by the ability of the triaxial-bulge model to explain the gross departures from the axially-symmetric rotational velocity field observed in this galaxy.

In conclusion, we have shown that purely geometrical evidence shows that bulges are triaxial, a conclusion also supported by dynamical evidence, which re-establishes the similarity between bulges and elliptical galaxies.

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References

Aarseth, S. J. and Binney, J. J., 1978. *Mon. Not. Roy. Astr. Soc.*, **185**, 227.
Bertola, F., 1972. in *Proc. 15th Meeting of the Ital. Astron. Soc.*
Bertola, F. and Capaccioli, M., 1975. *Astrophys. J.*, **200**, 439.
Bertola, F. and Galletta, G., 1979. *Astron. Astrophys.*, **77**, 363.
Bertola, F., Bettoni, D., Danziger, J., Sadler, E. M. and de Zeeuw, T., 1988, in preparation.
Boronson, T., 1981. *Astroph. J. Suppl. Ser.*, **46**, 177.
Capaccioli, M. and Vietri, M., 1988. *Mon. Not. Roy. Astr. Soc.*, in press.
Davies, R. L., 1987. in *Structure and Dynamics of Elliptical Galaxies*, I. A. U. Symp. 127, ed. T. de Zeeuw (Dordrecht: Reidel) p. 63.
Davies, R. L. and Birkinshaw, M., 1986. *Astrophys. J.*, **303**, L45.
Gamaleldin, A. I. and Issa, I. A., 1983. *Astron. Nachr.*, **304**, 21.
Gerhard, O. and Vietri, M., 1986. *Mon. Not. Roy. Astr. Soc.*, **223**, 377.
Gerhard, O. and Vietri, M., 1987, in *Structure and Dynamics of Elliptical Galaxies*, I. A. U. Symp. 127, ed. T. de Zeeuw (Dordrecht: Reidel) p. 399.
Illingworth, G., 1977. *Astrophys. J.*, **204**, 73.
Kormendy, J., 1982. *Astrophys. J.*, **257**, 75.
Lake, G., 1987, in *Structure and Dynamics of Elliptical Galaxies*, I. A. U. Symp. 127, ed. T. de Zeeuw (Reidel) p. 331.
Lauberts, A., 1982. *The ESO/Uppsala Survey of the ESO (B) Atlas* (ESO).
Lindblad, B., 1956. *Stockholm Obs. Ann.*, **19**, No. 2.
Schwarzschild, M., 1979. *Astrophys. J.*, **232**, 236.
Stark, A. A., 1977. *Astrophys. J.*, **213**, 368.
White, S., 1987, in *Structure and Dynamics of Elliptical Galaxies*, I. A. U. Symp. 127, ed. T. de Zeeuw (Dordrecht: Reidel) p. 339.
Zaritsky, D. and Lo, K. Y., 1986. *Astrophys. J.*, **303**, 66.

Simulations of High Redshift Galaxies and Observations with the Hubble Space Telescope

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The high angular resolution of the Hubble Space Telescope (HST) will allow the observations of the structure of small but extended objects. Prime candidates for this type of research are galaxies at moderate or high redshifts. These galaxies are approximately 1″ in diameter and will contain many resolution elements of the space telescope. The exact resolution will depend on the wavelength of the observation and on the mode in which the observations will be made, the highest resolution being obtained with the faint object camera in the f/288 mode. Since most imaging modes will provide a resolution better than ~0.″1, galaxies at large redshift will cover more than ~100 resolution elements. The Wide Field Camera (WFC) with a field of view of 3′ × 3′ is well suited for statistical studies of the properties of field galaxies, although its spatial resolution will be limited by the pixel size to .1″. The number of galaxies that can usefully be studied in each exposure naturally depends on the depth of the exposure, at V ~ 25 it is expected to be of the order of 100 galaxies.

In order to assess the potential of HST-WFC for the observation of random fields, we conducted a programme of simulations of galaxies and their "observations" with the WFC simulator developed at the ST-ECF (Rosa and Baade 1986). The starting point of our simulations was a set of 14 nearby galaxies of all Hubble types observed with the ESO Schmidt telescope, in the colours B and R, digitized and calibrated. U and V images were computed using a linear combination of the B and R images with coefficients based on a sample of multi-aperture photoelectric UBVR photometry. We shifted the galaxies to different distances, constructed a field of galaxies (3′ × 3′) and "observed" this field with the HST simulator.

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Individual Galaxies

We shifted the galaxies to different distances, scaling the angles as appropriate for a Friedmann cosmology with $q^{o} = 0$. The K-correction which needs to be applied to take the redshift into account was applied locally, pixel by pixel. This was done by calculating the colour of the individual pixels (the images were all shifted so that the centroid of the galaxy corresponded on all the frames taken for each galaxy). This colour was compared with the integrated colour of galaxies for which K-corrections are available (Coleman et al. 1980), and the K-correction of the standard galaxy with colour closest to the pixel colour was applied for the desired redshift. This procedure allows to correct the individual features of a galaxy, and hence to study the apparent evolution of the galaxy with redshift. No intrinsic evolution has been taken into account for the time being.

Our scheme to apply K-corrections has several shortcomings: Ideally the K-correction should be calculated for the individual components of a galaxy and applied to each component separately, the components being identified by their colour and location in the galaxy. In addition, reddening by dust in the galaxy modifies the spectrum of individual features and therefore the K-corrections that ought to be applied. Our procedure identifies the different

(continued on p. 30)

The centerfold shows a highly structured molecular cloud which is located in the southern constellation Norma, a region with many dark clouds. The cloud is clearly divided in two parts, a large irregular "head" and a long, thin "tail". The almost complete extinction of the rich background star fields in the Milky Way indicates that the clouds are very dense. Star formation is taking place at various points in the cloud, and two Herbig-Haro objects, HH 56 and HH 57, are found in the head. The energy source of HH 57 erupted just a few years ago in a so-called FU Orionis outburst, and is now a bright infrared source. This is one of the first star-forming