Bull. Astr. Soc. India (2000) **28**, 351-355

Lopsided spiral galaxies

Chanda J. Jog

Department of Physics, Indian Institute of Science, Bangalore 560 012, India

Abstract. The light distribution in disks of many spiral galaxies is non-axisymmetric or 'lopsided' with a spatial extent much larger along one half of a galaxy than the other, as in M101. Recent observations show that 30% of spiral galaxies have significant lopsidedness in both old stars and gas, indicating asymmetry in the disk mass distribution. This is a new and exciting area in galactic structure and dynamics. Here, first a brief review of observations will be given, and then the results from our theoretical work will be presented.

We have studied the dynamics of particles in closed orbits, the isophotes, and the local disk stability in an axisymmetric galactic disk perturbed by a lopsided halo potential. The results obtained are shown to be valid for both stars and gas in the same region of the disk. Our results naturally explain a number of observations of these galaxies, including the non-axisymmetric ($m = 1$) surface density distribution, the isophotal elongation, and the azimuthally asymmetric formation of HII regions. From the observed disk lopsidedness, the degree of halo lopsidedness is obtained to be ~ 5%. Our calculation of the self-consistent disk response shows that the resulting disk lopsidedness is important only beyond 1.4 disk scale-lengths and its magnitude increases with radius - this is exactly in agreement with the recent near-IR observations in the literature.

Key words : galaxies : kinematics and dynamics - galaxies : ISM - galaxies : spiral - galaxies : individual : M101 - HII regions

1. Lopsided galaxies : introduction

It has been known for a long time that the light and hence the mass ditribution in disks of spiral galaxies is not strictly axisymmetric, as for example in M101 (NGC 5457) and in NGC 1637 (Sandage 1961), where the isophotes are elongated in one half of the galaxy. Thus, these galaxies display a globally non-axisymmetric spatial distribution of type $m = 1$, where m is the azimuthal wavenumber, or a $\cos\phi$ distribution where ϕ is the azimuthal angle in the plane of the disk. Despite this, astronomers have largely tended to ignore it because it is much simpler to study the dynamics of axisymmetric disks.

This phenomenon was first highlighted in a classic paper by Baldwin, Lynden-Bell & Sancisi (1980) who studied galaxies which had highly asymmetric spatial extent of atomic hydrogen gas distributions in the outer regions in the two halves of a galaxy, such as M101, IC 342 (see their Fig. 1). They gave an apt name *lopsided* to these galaxies. Further HI mapping studies were done by Phookun, Vogel & Mundy (1993) for the special case of one-armed galaxies such as NGC 4254 where the phase varies with radius (see Section 2.2). Recent work based on the global HI velocity profiles of a much larger sample of galaxies by Richter & Sancisi (1994), and Haynes et al. (1998) shows that nearly 50% of galaxies show a lopsided distribution.

An exciting new development in this area is the imaging studies of spiral galaxies in the near-IR K-band (2.2 μ) made possible by the NICMOS 3 array (Rix & Zaritsky 1995, Zaritsky & Rix 1997). The dust extinction effects are negligible in this band, hence these studies reveal the spatial distribution of the underlying old stellar population. These authors detected a non-axisymmetric $m = 1$ distribution of surface density of old stars in the inner / optical region of the disk. Rix & Zaritsky (1995) define A_1/A_0, the fractional amplitude of the first azimuthal fourier component ($m = 1$) of surface brightness, to be the quantitative measure of disk asymmetry; and they find that A_1/A_0 increases with radius, and is large ≥ 0.2 at the outermost point of detection for 30% of the galaxies studied.

Thus, *lopsided distribution in the disk is a general phenomenon*. Hence it is important to understand the dynamics of lopsided galaxies. This is the motivation for our theoretical work (Jog 1997, 1999 a), described briefly in Sections 2-3.

The origin of the $m = 1$ distribution in the disk has not been studied much theoretically until recently. Tidal interaction (Beale & Davies 1969), and satellite galaxy accretion (Rix & Zaritsky 1995) have been suggested as the origin of the disk lopsideness. Weinberg (1995) has shown that the tidal interaction between the Galaxy and the LMC leads to a lopsided distortion of the Galaxy halo at resonance points between the LMC and the halo orbit frequencies, which in turn causes a lopsided distribution in the disk of the Galaxy. Since galaxy interactions are now known to be common, we assume the above to be a general mechanism for causing a lopsided distortion in the halo and that it is a long-lived phenomenon lasting for times greater than dynamical timescales.

2. Orbits and isophotes in a lopsided potential

The study the dynamics of particles on closed orbits and the local disk stability in an axisymmetric disk perturbed by a lopsided halo potential (Jog 1997), the highlights of the results from this work are given below. The cylindrical coordinate system (R, ϕ) in the galactic disk plane is used.

2.1 Orbits in a lopsided potential

The unperturbed, axisymmetric potential in the disk plane, Ψ_0, is chosen to be :

$$\Psi_0(R) = V_c^2 ln R \qquad (1$$

This is applicable for a region of flat rotation, with V_c being the constant rotational velocity, as seen in a typical spiral galaxy.

This is perturbed by a small, non-rotating, halo lopsided potential :

$$\Psi_{lop}(R) = V_c^2 \epsilon_{lop} cos\phi \tag{2}$$

where ϵlop is a small perturbation parameter, which is taken to be constant with radius for simplicity. That is, we assume a halo with a constant lopsided distortion.

Consider a circular orbit at R_0. The coupled equations of motion for the perturbed quantities δR and $\delta\phi$ are solved together using the first-order epicyclic theory. The resulting solutions for the perturbed motion are :

$$R = R_0 \,(1 - 2\epsilon_{lop}\, cos\phi) \; ; \quad V_{\mathbf{R}} = 2V_c\, \epsilon_{lop}\, sin\phi \; ; \quad V_\phi = V_c\,(1{+}3\, \epsilon_{lop} cos\phi) \tag{3}$$

Thus, an orbit is elongated along ϕ = 180°, that is along the minimum of the lopsided potential, and it is shortened along the opposite direction.

The kinematics in the disk is also strongly affected. The net rotational velocity, V_ϕ, (see eq. (3)), is a maximum at ϕ = 0°, and it is a minimum along the opposite direction. This results in distinctly *asymmetric rotation curves* in the two halves of galaxy (Jog 1997), with the maximum difference between the rotational velocities = $6\epsilon_{lop} Vc$, whihc is ~ $0.2\ V_c$ for the typical observed A_1/A_0 values (Jog 1999 b). This explains the long-standing puzzle of the observed asymmetry in rotation curves of galaxies such as M101. Such asymmetry has also been studied by Swaters et al. (1999) from their recent kinematic data on DDO 9 and NGC 4395.

Here we have considered closed orbits for simplicity. The orbits would change slightly and would not be closed if the random motion of the particles is taken into account. However, this does not effect the isophotal shapes - see Section 2 of Jog (1997) for details of this subtle point.

2.2 Isophotes in an exponential disk

Since the imaging observations give information on the isophotes rather than orbits, we also obtain the isophotal shapes in an exponential galactic disk in a lopsided potential. For an exponential disk, we show that :

$$A_1/A_0 = \frac{\epsilon_{iso}}{2} \; \frac{R}{R_{exp}} \tag{4}$$

where ϵ_{iso} is the ellipticity of the isophote at R, and R_{exp} is the exponential disk scale length. Note that here the radii measuring the minimum and maximum extents of an isophote are along the same axis - unlike in the standard definition of ellipticity where these two are along directions that are normal to each other. *The resulting isophotes have an egg-shaped oval appearance*, as observed say in M101, and NGC 1637. Thus, the azimuthal asymmetry in the surface density as denoted bhy A_1/A_0 manifests itself as an elongation of the isophotes, and both represent the same underlying phenomenon.

The isophotal shapes in a lopsided potential are obtained next by solving the equations of perturbed motion (eq. (3)), the equation of continuity, and the effective surface density; and this gives the following important result (valid for $R \geq R_{exp}$)

$$\epsilon_{iso}/\epsilon_{lop} = 4\left(1 + \frac{R_{exp}}{2R}\right) \tag{5}$$

Thus, the ellipticity of isophotal contours is *higher by at least a factor of* 4 compared to ϵ_{lop}. *Thus even a few % asymmetry in the halo potential leads to a large spatial lopsidedness in the disk* - this makes the detection of lopsideness easier, and it explains why a large fraction of spiral galaxies is observed to be lopsided.

For the typical observed values of $A_1/A_0 \geq 0.2$ at $R/R_{exp} = 2.5$ (see Section 1), we obtain typical $\epsilon_{lop} \sim 0.03$ (from eqs. (4), and (5)), or ~ 0.05 in view of the negative disk response (Section 3). Thus, from the observed disk lopsidedness, we obtain a value of the *halo lopsidedness.*

In the limiting case of high observed $A_1/A_0 \sim 0.3 - 0.4$, the resulting ϵ_{lop} is still small ≤ 0.1, this is due to the high ratio of $\epsilon_{iso}/\epsilon_{lop}$ (eq.(5)). This is an interesting result, because physically it means that despite the visual asymmetry, such galaxies are dynamically robust.

The above results for orbits and isophotes are shown to be applicable for both stars and gas in the same region of the galaxy since they respond to the same lopsided potential and have comparable exponential disk scale lengths (Jog 1997). We show that in fact the data on the molecular gas, H_2, in the literature- say in M101, and NGC 4565, do show evidence for a lopsided distribution.

We have also obtained results for a general power law rotation curve, and when the phase of the potential has a radial dependence. When the phase varies with radius, the resulting isophotes show a prominent one-arm, as observed in M51 and NGC 2997.

2.3 Local gas stability in a lopsided potential

The effective surface density is shown to be a maximum at $\phi = 0°$, corresponding to an overdense region, while there is an underdense region in the opposite direction along $\phi = 180°$. The fractional increase in surface density at $\phi = 0°$ is high ~ 0.3 – 0.5 for strongly lopsided galaxies (see Fig. 1, Jog 1997). Thus, the molecular gas in the overdense region could become unstable and result in enhanced star formation.

To study this, we further obtained an effective Q criterion for the local disk stability for the velocity field in a lopsided potential. It was shown that in the overdense region, the effective Q value is less than the standard axisymmetric value. Since the gas is close to neutral equilibrium to begin with, this leads to an azimuthally asymmetric star formation in the disk - as we have shown for example for the parameters for M101. Further, the enhanced star formation in the overdense region is argued to give rise to a preferential formation of massive stars (Jog & Solomon 1992), resulting in more HII regions there - this is exactly in agreement with observations of more HII regions along the SW in M101. A more quantitative study of this problem is under progress (Jog 1999 b).

3. Disk response : self-consistent calculation

The above result that the disk density response is a maximum along $\phi = 0°$, that is along the maximum of the lopsided potential (eq.(2)); has interesting and subtle dynamical consequences which we have studied in Jog (1999 a), as briefly described next. The self-gravitational potential corresponding to the non-axisymmetric disk response is obtained by inversion of Possion equation for a thin disk, using the Henkel transforms of the potential-density pairs. This is shown to oppose the imposed lopsided potential. A self-consistent calculation shows that the net lopsided distribution in the disk is only important beyond 1.4 disk scale lengths and its magnitude increases with radius, indicating the increasing dynamical importance of halo over disk at large radii. The negative disk response decreases the imposed lopsided potential by a factor of ~ 0.5–0.7. The above radial dependence is robust and agrees very well with the near-IR observations of Rix & Zaritsky (1995). For the details, see Jog (1999 a).

4. Summary

We have studied the dynamics in an axisymmetric galactic disk perturbed by a lopsided halo potential, and our results naturally explain several observations of lopsided galaxies, such as the non-axisymmetric ($m = 1$) disk surface density, isophotal elongation, asymmetric star formation in the disk, and the increasing disk lopsidedness at large radii.

Here, we have stressed the lopsided case ($m = 1$). Similarly, higher order ($m = 2$, 3 etc.) cases of global asymmetry have recently been observed in the near-IR (for stars) and in HI (e.g, Rix & Zaritsky 1995; Schoenmakers, Franx, & de Zeeuw 1997; Kornreich, Haynes, & Lovelace 1998).

In summary, the study of asymmetry is an emerging and a challenging area in galactic structure and dynamics, with lots of open questions - both observational and theoretical.

References

Baldwin J.E., Lynden-Bell D., Sancisi R, 1980, MNRAS, 193, 313
Beale J.S., Davies R.D. 1969, Nature, 221, 531
Haynes M.P. et al. 1998, AJ, 115, 62
Jog C.J. 1997, ApJ, 488, 642
Jog C.J. 1999 a, ApJ, In press
Jog C.J. 1999 b, in preparation
Jog C.J., Solomon P.M. 1992, ApJ, 387, 152
Kornreich D.A., Haynes M.P., Lovelace R.V.E. 1998, AJ, 116, 2154
Phookun B., Vogel S.N., Mundy L.G. 1993, ApJ, 418, 113
Richter O.-G., Sancisi R. 1994, A & A, 290, L9
Rix H.-W., Zaritsky D. 1995, ApJ, 447, 82
Sandage A, 1961, The Hubble Atlas of Galaxies (Washington: Carnegie Institution of Washington)
Schoenmakers R.H.M., Franx M., de Zeeuw P.T. 1997, MNRAS, 292, 349
Swaters R.A. et al. 1999, MNRAS, submitted (astro-ph/9811424)
Weinberg M.D. 1995, ApJ, 455, L31
Zaritsky D. Rix H.-W. 1997, ApJ, 477, 118