The Origins of Disk Heating

Michael R. Merrifield
School of Physics & Astronomy, University of Nottingham, Nottingham, NG7 2RD, England

Joris Gerssen and Konrad Kuijken
Kapteyn Institute, PO Box 800, 9700 AV Groningen, The Netherlands

Abstract. By making spectral absorption-line observations of disk galaxies at intermediate inclinations, we have been able to determine the amplitude of their constituent stars’ random motions in three dimensions. This full measure of the shape of the velocity ellipsoid is a useful diagnostic for determining the “heating” mechanism responsible for creating the random motions. The analysis implies that the main heating process varies with galaxy type, with minor mergers dominating the heating in early-type disk galaxies, and spiral density waves the most important mechanism in late-type systems.

1. Introduction

Observations of edge-on galaxies reveal that they are remarkably thin structures, but not infinitely so. Their finite extent perpendicular to the disk plane can be attributed to the excursions that stars take in this direction due to their random motions. Stars are born in a very thin layer of gas in these galaxies, which, due to its collisional nature, has very little by way of random motions. Thus, stars must acquire their random velocities in later life, and several candidates have been suggested for the source of this “heating.” One way that a star can acquire such a random component is by scattering gravitationally from a more massive object, such as a giant molecular cloud. Similarly, the mass enhancements associated with spiral density waves can gravitationally scatter stars. Finally, the heating could be due to an external source, such as a small satellite galaxy colliding with the disk; the energy dissipated in such a collision would significantly heat the original stellar population.

How, then, does one distinguish between these possibilities? One very useful diagnostic is provided by the relative amplitudes of the random motions in different directions (Jenkins & Binney 1990). Scattering off giant molecular clouds is a very stochastic process, so heats the population reasonably isotropically. Density waves, on the other hand, are encountered in a more predictable fashion. Since two-armed spirals tend to be most common, a star will receive a kick from the associated density wave twice per orbit. This frequency is close to the star’s natural oscillation frequency in the radial direction, so random motions in this direction will be increased rapidly by this near-resonant process, making the
radial velocity dispersion, $\sigma_R$, significantly greater than the velocity dispersion perpendicular to the plane, $\sigma_z$ (Jenkins & Binney 1990). Finally, mergers with satellites couple closely to oscillations that can be excited perpendicular to the disk plane, so such heating events would enhance $\sigma_z$ relative to $\sigma_R$ (Sellwood, Nelson & Tremaine 1998). Thus, measuring the ratio of $\sigma_z/\sigma_R$ offers a simple test for determining the cause of the random motions.

The main complication in applying this diagnostic in practice is that it is difficult to measure $\sigma_R$ and $\sigma_z$ simultaneously. Since Doppler broadening of spectral lines only enables one to determine the line-of-sight velocity dispersions of external galaxies, $\sigma_z$ is usually only measured for face-on galaxies while $\sigma_R$ is only observed in edge-on systems (e.g. van der Kruit & Freeman 1986). The only exception to this problem is the Milky Way, where one can measure the full three-dimensional motions of nearby stars from their Doppler shifts and proper motions.

However, we have now shown that one can also determine the random velocities in all three dimensions for some external galaxies. If one picks a disk galaxy at intermediate inclination, then observations of the line-of-sight velocity dispersion along its minor axis are a combination of $\sigma_R$ and $\sigma_z$, while measurements along its major axis reveal a combination of $\sigma_z$ and the remaining component, $\sigma_\phi$, the velocity dispersion in the tangential direction. One then invokes the fact that these quantities are also related by the equations of stellar dynamics (Binney & Tremaine 1987); specifically, the asymmetric drift equation relates $\sigma_R$ to the mean rotation speed of the stars, $\Upsilon$, and the local circular speed, $v_c$. The former of these quantities can be obtained from the Doppler shift in spectral absorption lines along the major axis, while the latter can be obtained from the Doppler shifts in any emission lines, which arise from gas on circular orbits. For an exponential disk of scalelength $h_d$, the asymmetric drift equation can be written

$$v_c^2 - \Upsilon^2 = \sigma_R^2 \left[ \frac{R}{h_d} - \frac{R}{\partial R} \ln(\sigma_R^2) - \frac{1}{2} + \frac{R}{2v_c} \frac{\partial v_c}{\partial R} \right]. \tag{1}$$

Combining this equation with the two observable quantities (the line-of-sight kinematics along the major and minor axes), one can solve for all three components of the velocity dispersion, $\sigma_R$, $\sigma_\phi$, and $\sigma_z$.

Even with the best data available today, one cannot perform this analysis in a completely non-parametric fashion. Instead, one adopts a somewhat simplified model in which the ratios of the dispersions remain fixed. By solving for the free parameters in this model, one in essence obtains average values for ratios such as $\sigma_z/\sigma_R$, and hence a measure of what globally is the most important heating mechanism in the galaxy.

2. Results

As mentioned above, by looking at nearby stars, one can determine all three components of the velocity dispersion of the Milky Way in the solar neighbourhood. This analysis reveals a ratio of $\sigma_z/\sigma_R \sim 0.53$ (Dehnen & Binney 1998). Such a low value is consistent with what one would expect for a galaxy in which spiral density waves are the major heating mechanism.
By observing kinematics along the major and minor axes of NGC 488, and using the technique described in the previous section, we made the first comparable measurement for an external galaxy (Gerssen, Kuijken & Merrifield 1997). Fitting to these data (shown in Fig. 1) reveals a higher ratio of $\sigma_z/\sigma_R \sim 0.7$. This galaxy is of an earlier type than the Milky Way (Sb as opposed to Sbc), with correspondingly weaker spiral structure. It is also bright in CO emission (Young et al. 1995), implying that it is rich in molecular clouds. It is therefore not too surprising that the $\sigma_z/\sigma_R$ diagnostic favours molecular clouds over density waves as the source of the heating in this case.

More recently, we have made a similar analysis of the Sab galaxy NGC 2985 (Gerssen, Kuijken & Merrifield 2000). The even earlier type of this galaxy implies that spiral density waves are unlikely to have a significant role to play, but the absence of strong CO emission also makes molecular clouds implausible sources of disk heating. It is therefore interesting that the analysis of this galaxy returns a ratio of $\sigma_z/\sigma_R \sim 0.85$. Such an extreme value strongly favours the third possibility, mergers with satellites, as the heating mechanism.

With three measurements, we can start to look for any systematic trends. As Fig. 2 shows, there is some evidence for such a trend: the earlier the Hubble type of the galaxy, the larger the value of $\sigma_z/\sigma_R$. Galaxy interactions provide a plausible explanation for this correlation: in addition to enhancing the value of $\sigma_z/\sigma_R$, mergers are likely to transform galaxies to earlier Hubble types. However, the large error bars on Fig. 2 mean that any such interpretation should be viewed with caution. The modelling process required to calculate $\sigma_z/\sigma_R$ is quite...
Figure 2. Plot showing the velocity dispersion ratio, $\sigma_z/\sigma_R$, as a function of Hubble type for the three galaxies for which this quantity has now been determined. The error bars show the uncertainties in these two quantities, and the “postage stamp” images at the centres of each error bar illustrate the galaxies’ morphologies.

complex and results in a rather uncertain estimate, and even the definition of a galaxy’s Hubble type has significant uncertainty due to the subjectivity of the classification. Thus, the tight correlation between these quantities must be somewhat fortuitous. Clearly, $\sigma_z/\sigma_R$ needs to be measured for a larger sample of galaxies before any general conclusions can be drawn, but even these preliminary results show the promise of this technique for uncovering the origins of disk heating.

References

Binney, J. & Tremaine, S. 1987, Galactic Dynamics (Princeton: Princeton University Press)
Dehnen, W. & Binney, J. 1998, MNRAS, 298, 387
van der Kruit, P.C. & Freeman, K. 1986, ApJ, 303, 556
Gerssen, J., Kuijken, K. & Merrifield, M.R. 1997, MNRAS, 288, 617
Gerssen, J., Kuijken, K. & Merrifield, M.R. 2000, MNRAS, in press
Jenkins, A. & Binney, J. 1990, MNRAS, 245, 305
Sellwood, J.A., Nelson, R.W. & Tremaine, S. 1998, ApJ, 506, 590
Young, J.S., et al. 1995, ApJS, 98, 219