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Kinematics of molecular gas in the nucleus of barred galaxies : NGC 253 and M82

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Abstract. In more than half of all observed spiral galaxies, the central molecular gas is distributed in a bar. Since gas is a dissipative fluid, it will tend to settle along closed orbits in the plane of a galaxy. Simulations of bar orbits have shown that there are mainly two types of closed orbits in a bar potential the x1 orbits lying along the length of the bar and the x2 orbits lying perpendicular to the length of the bar. We have used a simple form of a bar potential to model the bar in two nearby starburst galaxies, NGC 253 and M82. Using parameters taken from the observed rotation curves, we have constructed the position velocity diagram and velocity contour plot for the bar in these galaxies. These plots help us understand the observed distribution and velocity field of the gas in these galaxies. We find that in NGC 253, the nuclear star formation is concentrated mainly along the x2 orbits and the nuclear velocity field shows signs of a past merger event in the galaxy. In M82, we find that the supernova remnants and HI gas lies along the x1 orbits whereas the ionized gas is mainly along the inner x2 orbits.

Key words : galaxies : individual (NGC 253, M82), ISM : kinematics and dynamics

1. Introduction

About two thirds of all spiral galaxies are barred. Bars are ellipsoidal but flattened systems and as a result many bars can be modelled as prolate systems with two minor axes of the same length. The stars and gas move along orbits within the rotating bar. Though the rotation curves of both barred and non-barred galaxies are similar, their isovelocity contours are very different. An axisymmetric velocity field has velocity contours in the form of the familiar 'Spider Diagram' whereas the velocity field of a bar has an elongated 'S' shaped structure which clearly lies along the direction of the bar (Combes et al. 1991). In this paper we discuss how the velocity field of the gas in a bar can be understood as being due to gas moving on closed orbits within a barred potential. We also apply our model to understand the velocity field of gas in the bar of two nearby starburst galaxies, NGC 253 and M82.

2. Gas Moving in a Barred Potential

Gas clouds dissipate energy through collisions. Hence clouds will tend to move along closed orbits in a plane. In a bar potential there are mainly two types of closed orbits in the plane of the galaxy; the x1 (bar) orbits which are extended along the major axis of the bar and the x2 (antibar) orbits which are oriented perpendicular to the major axis of the bar. At the intersection of the x1 and x2 orbits, gas clouds may collide, lose angular momentum and sink into the x2 orbits. Simulations of gas evolution in bars have shown that an evolved bar has relatively more gas on the inner orbits than on the outer orbits. This method of explaining gas kinematics in a barred potential was first introduced by Binney et al. (1991) who used it to explain the distribution of gas in the centre of our Galaxy. We have used a similar approach to model the velocity field of two galaxies, NGC 253 and M82. For simplicity we have adopted a logarithmic bar potential to model the velocity field. The potential is given by,

$$\Phi(x,y) = \frac{1}{2}(v_b)^2 ln(x^2 + \frac{y^2}{q^2} + R_c^2) \tag{1}$$

where v_b is the velocity in the flat portion of the rotation curve of the galaxy, q is the non-axisymmetry parameter and R_c is the core radius. We have used a value of q=0.8 for our model of the bar in NGC 253 and M82 since this value of q gives a large number of non-self intersecting x1 and x2 orbits. The choice of q is not unique, the range of values which give a similar bar structure is $0.7 < q < 0.9$. The core radius R_c was chosen so that distinct x1 and x2 orbits were obtained. The choice of this parameter is also not unique; there is an upper limiting value only below which we obtain a range of x1 and x2 orbits. For example, in NGC 253 $R_c < 200$pc. However, R_c has to be large enough to result in the elongation of the isovelocity contours along the bar length and not the familiar "spider diagram" seen in the velocity field of non-barred spiral galaxies. In order to compare the model velocity field with that observed, it is necessary to project the closed orbits onto the plane of the sky. The projected length of a vector in the sky l_{obs} is related to the actual length in the plane of the galaxy l_{gal} by

$$l_{obs} = l_{gal}\sqrt{cos^2\phi + sin^2\phi cos^2 i} \tag{2}$$

where ϕ is the angle between the length l_{gal} and the galaxy axis in the plane of the galaxy and i is the angle of inclination of the galaxy. The projection of the angle ϕ onto the plane of the sky is given by ϕ' where

$$tan\phi' = tan\phi . cos i \tag{3}$$

To obtain the velocity field of the bar model we need to determine the radial velocity at each point along the closed orbits. The radial velocity is given by,

$$v_{rad} = [(v_x - \Omega_{b}y)sin\phi + (v_y + \Omega_b x)cos\phi]sin(i) \tag{4}$$

Using equation (4), it is possible to plot isovelocity contours for the radial velocities of the closed bar orbits projected onto the plane of the sky.

3. The model velocity field

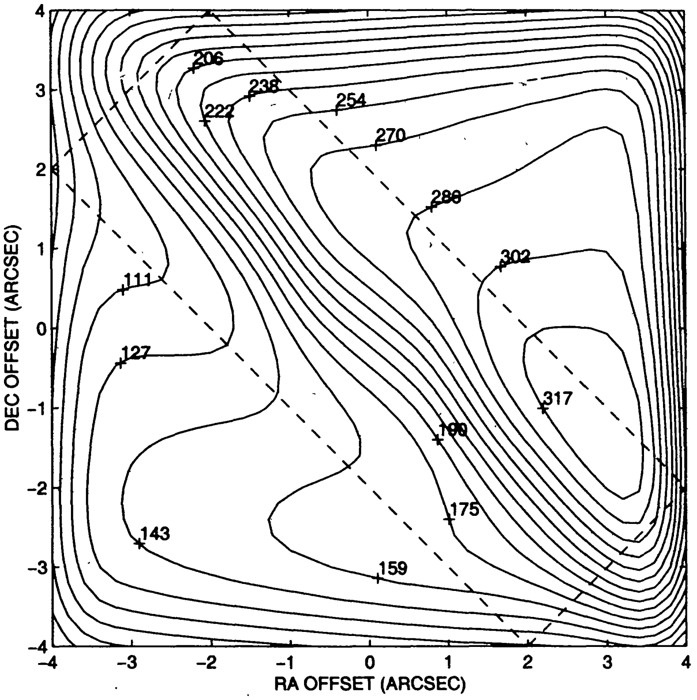
We can derive both the isovelocity contour plot and the position velocity (P-V) plot from the closed orbits in a bar potential. When deriving the isovelocity contours of the closed orbits we have to keep in mind that the observed field is the result of convolving the sky image with the telescope beam. Hence we convolved the velocity field derived from the model with a two dimensional gaussian having parameters similar to that of the telescope beam. We used a software package called SURFER to determine the radial velocities along the closed orbits over a two dimensional grid on the plane of the sky. The two dimensional grid was then convolved with a two dimensional matrix representing the gaussian beam of the telescope.

The observed P-V diagram reveals how the radial velocity of the gas varies over that region. There is, however, an important difference between the observed and model plots. In the observed P-V diagram, the velocity spread Δv due to internal random motion or expansion of the gas is included. But in the model velocity diagram, only the central rotational velocity v_o is plotted. So an agreement is expected only when the line width is small, e.g. cold gas with little or no turbulence. For $\frac{\Delta v}{v_o} < 1$, we get fairly good agreement between the observed and model P-V plots.

4. Velocity field of NGC 253

Figure 1 shows the model isovelocity field within the inner 8″ derived from the closed orbits. The convolving gaussian function used in our modelling has a size 1″ x 1.8″ which is the same resolution as the beam used by Anantharamaiah & Goss (1996) in their H92α observations. When we compared this velocity field with Figure 1b of Anantharamaiah & Goss (1996) we find a remarkable correspondence between the observed and model velocity fields in the central region. The S-shape pattern in the observed field is also present to some extent in the model velocity field. It thus appears that most of the ionized gas observed in the H92α line is in the x2 orbits of the bar potential. However at larger scales of 54″x30″, the CO velocity field observed by Yun (1999), does not match the model isovelocity field very well. Since the difference is not very large, we conjecture that there is some perturbation within the bar which is causing the change in bar direction as we go to progressively larger radii. This change in the position angle of the bar with radius has been observed by Baan, Bragg, Henkel and Wilson (1997) in the formaldehyde absorption line. We suggest that this perturbation of the bar potential could have been caused by a merger event in the recent history of the galaxy.

Figure 2 shows the model P-V diagram for the inner region of the bar. This figure can be compared with Figure 6b of Peng et al. (1996) which is constructed using the CS line from molecular gas in the central 45″ of NGC 253. There is good agreement between the model and observations indicating that in addition to ionized gas, there is also a significant amount of molecular gas in the x2 orbits. This gas is cool enough for the relation $\frac{\Delta v}{v_o} < 1$ to be satisfied. However the P-V plot constructed from the H92α RRL emission data compares only fairly well with the model; there is a large velocity spread in the observed figure which is not there in the



Figufre 1. Isovelocity contours of gas motion in the central 8″, constructed from the closed orbits in the model bar potential for the galaxy NGC 253. The grid resolution is 1″x 1.8″, which is equal to the beam resolution of the H92α observations of Anantharamaiah & Goss (1996)

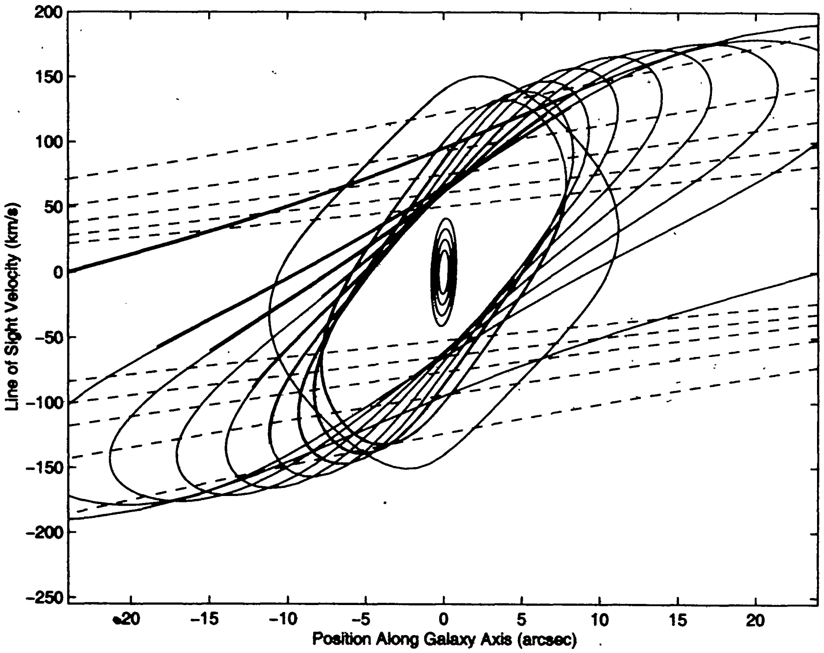


Figure 2. Position velocity (P-V) diagram of the gas moving along the closed orbits in the inner 45″, constructed from the closed orbits in the model bar potential of NGC 253. The dashed lines represents the bar (x1) orbits and the solid lines represents the antibar (x2) orbits.

observations. We feel this is because the line width of spectral lines emitted from hot gas is large compared to say neutral gas which is much colder (for more details see Das & Anantharamaiah, 1999).

5. Velocity field of M82

We have modelled the velocity field of M82 in a similar manner. Using the rotation curve parameters, we have determined the closed orbits and constructed the P-V diagram for the bar in M82. The model was compared with the observational P-V plot of M82. This was constructed from the neutral hydrogen absorption lines measured against the SNR's in the bar (Wills, Das, Pedlar & Muxlow 1999). We find a very good correspondence between the model and observed P-V plots. The plot shows that most of the supernova remnants in M82 are concentrated on the x1 orbits. This region is also rich in neutral hydrogen. There is considerable amounts of ionized gas on the inner x2 orbits. These results indicate that star formation is moving inwards onto the x2 ring.

6. Conclusion

We have used the theory of closed orbits in a barred potential to understand the gas motion in two nearby starburst galaxies, NGC 253 and M82. We have used a simple logarithmic potential to model the bar. The parameters were derived from the observed rotation curve of these galaxies. We determined the isovelocity contours and the position velocity plots from the x1 and x2 orbits in the model bar potential and compared them with the observed velocity fields. We obtain a good correspondence between the model velocity field of the nuclear gas and that observed. This shows that dense gas and star forming regions are located on the x1 and x2 orbits in the bars of these galaxies. Also, in NGC 253, the isovelocity contours are perturbed at larger scales in the bar. We propose that this may be due to a recent accretion event in the galaxy, which in turn triggered the starburst in the galaxy.

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