PASJ: Publ. Astron. Soc. Japan **50**, 227–231 (1998)

Is M82 a Disk-Truncated Bulge by a Close Encouter with M81?

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(Received 1997 October 28; accepted 1998 February 25)

Abstract

The rotation curve of the small-mass starburst galaxy M82 has a steep nuclear rise, peaking at 200 pc radius, which then declines in a Keplerian fashion. This rotation curve mimics that for a central bulge of spiral galaxies with a high concentration of stellar mass. The declining rotation indicates that its extended disk mass is missing. In order to explain this peculiar rotation characteristic, we propose a hypothesis that M82 is a surviving central bulge of a much larger disk galaxy, whose outer disk was truncated during a close encounter with M81. We simulated a tidal truncation of the disk of a companion galaxy by a tidal penetration through its more massive parent galaxy. The model can well reproduce the observed peculiar feature of M82.

Key words: Galaxies: bulges — Galaxies: collision — Galaxies: interaction — Galaxies: starburst

1. Introduction

CO observations of the starburst galaxy M82 with high-resolution and high sensitivity have indicated a prominent concentration of molecular gas in the central starburst region as well as a gas disk toward the optical edges (Nakai et al. 1987; Lo et al. 1987; Loiseau et al. 1990; Sofue et al. 1992). Various peculiar properties associated with the high concentration of molecular gas have been claimed to exist (Rieke et al. 1980; Telesco et al. 1991; Nakai et al. 1987; Sofue 1988). Kinematically, a declining rotation in the outer disk was found obviously in this galaxy (Young, Scoville 1984), and a Keplerian rotation has been suggested (Sofue et al. 1992). M82 also has an extended H I tail, indicating a strong interaction with the giant spiral M81 (Cottrell 1977; Gottesman, Weliachew 1977; Appleton et al. 1988; Brouilet et al. 1991). Moreover, high-resolution VLA observations in the H I line emission have provided an accurate position–velocity diagram in the outer disk (Yun et al. 1993).

In this paper we discuss our investigations of these CO and H I position–velocity data to obtain an accurate rotation curve of M82, and discuss the Keplerian rotation, which is very peculiar and exceptional for a disk galaxy. Rotation curves are the principal tool used to analyze the kinematics and mass of galaxies, and have been extensively investigated based on optical (Hα) and H I-line data for the outer disks (Rubin et al. 1982; Persic et al. 1996), and on CO-line data for the nuclear regions (Sofue 1996, 1997). However, no galaxy, except for M82, has been known to exhibit a Keplerian-like declining rotation within a few kpc radius. In order to explain the peculiar kinematics, we simulated the tidal interaction between M82 and M81, and propose a tidal truncation model of M82's outer disk. The distance to M82 is assumed to be 3.25 Mpc (Tamman, Sandage 1968).

2. CO and H I-Line Rotation Curves

Figure 1 shows a superposition of the highest-resolution position–velocity diagrams in the CO ($J = 2$–1) (Sofue et al. 1992) and H I-line emission (Yun et al. 1993). It is remarkable that the H I and CO emission regions are well mixed. Note that the brightest region in CO in the central 0.5 kpc is observed in absorption in the H I line. Such a mixed existence of H I and CO is quite unique, different from the common interstellar property in other galaxies, where H I and CO gases are more clearly separated by a molecular front (Sofue et al. 1994; Honma et al. 1995).

The most prominent kinematical feature observed in figure 1 is the declining rotation velocity. In order to obtain the rotation curve, we applied an envelope-tracing method (Sofue 1996, 1997) to this diagram; the result is shown in figure 2 by the thick line. The dotted thin line in figure 2 shows an H I rotation curve, as obtained from an intensity-averaged velocity field of H I gas (Yun et al. 1993), which indicates slightly slower values than those from the envelope-tracing. Also note that the H I data beyond 4′ are only for the north-eastern side. Beyond 5′ radius, the galaxy has no clear disk component, and it is difficult to trace any sysetematic velocity variation as a function of the radius, being merged by the distorted H I envelope (Cottrel 1977; Gottesman, Weliachw 1977; Yun et al. 1993).

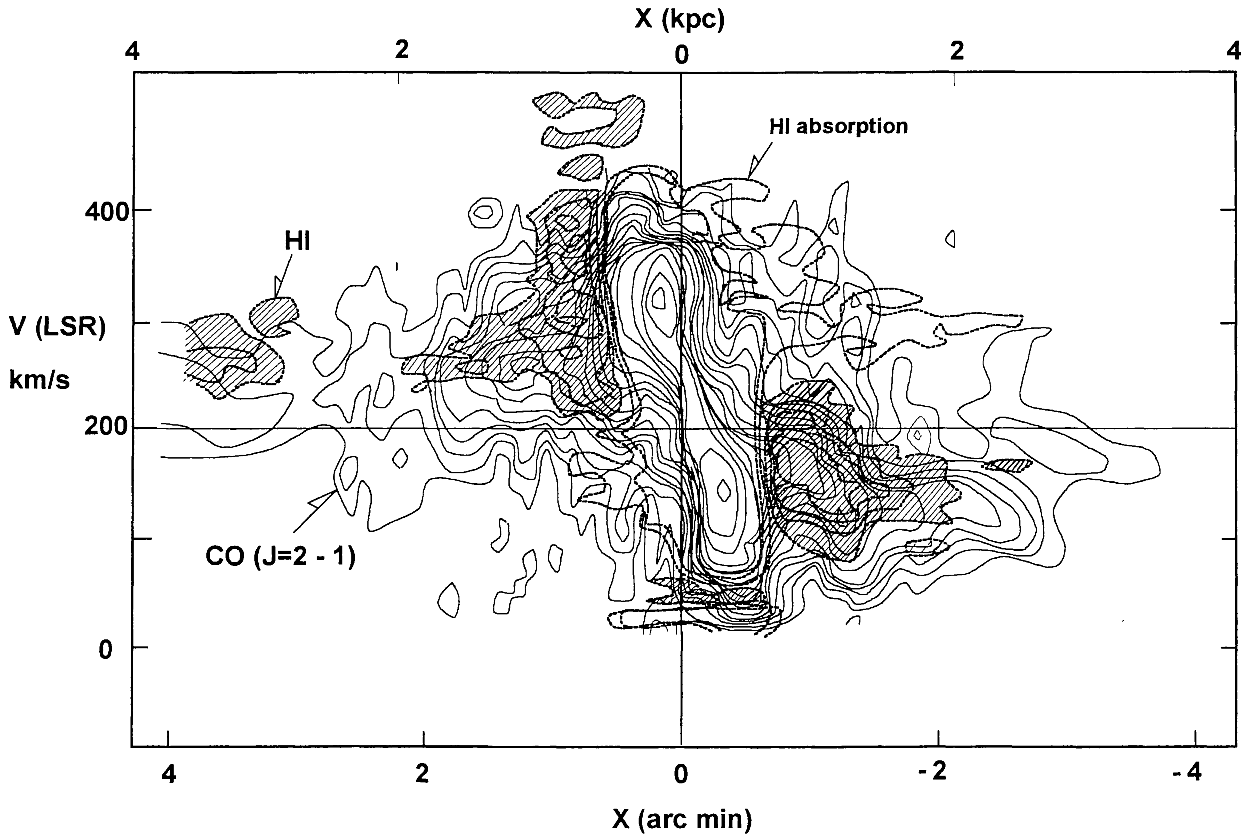

Fig. 1. Position–velocity diagram along the major axis of M82 in CO (J = 2–1) (thin contours), superposed on that in H I (hatched).

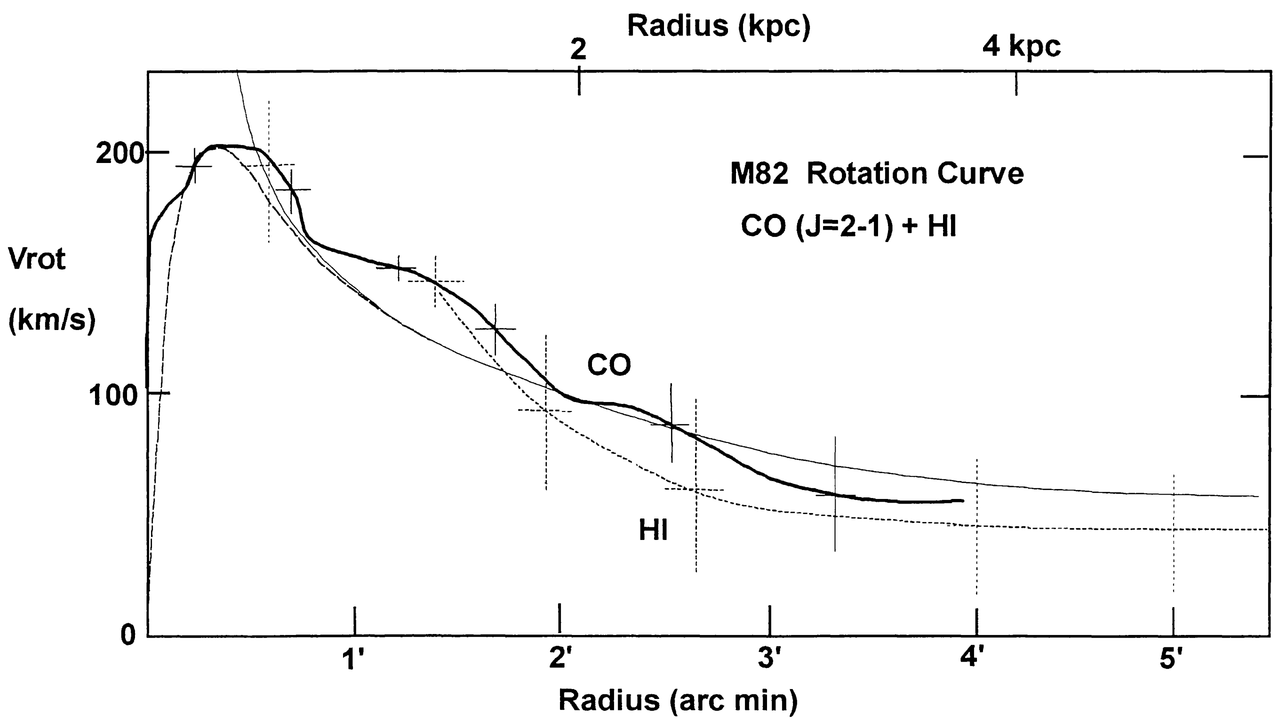

Fig. 2. Rotation curve of M82. The rotation velocities for a point mass (thin line) and an exponential-surface density sphere (dashed line) are indicated.

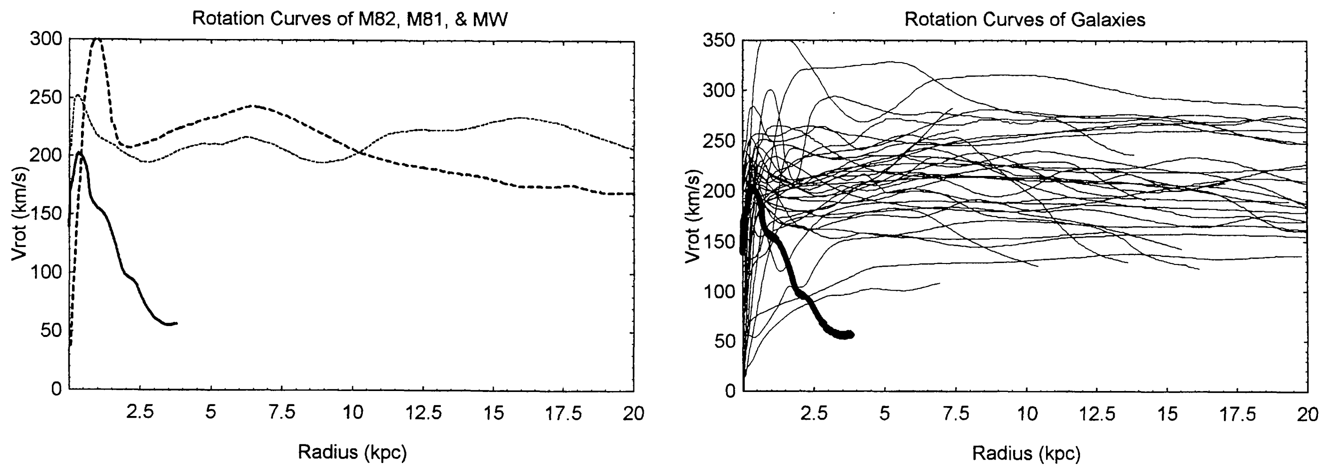

Fig. 3. Rotation curve of M82 (full line) compared with those of M81 (dashed line) and the Milky Way (dotted line), as well as with those for other spiral galaxies (thin lines).

The rotation velocity of M82 increases steeply, and attains a sharp maximum at 200 pc radius. The rotation velocity then declines monotonically to a velocity of as low as 50 km s^{-1} at 4 kpc radius. It is not likely that this behavior is due to warping of a disk with flat rotation, because the galaxy is almost edge-on, and there is no sign of any strong warping to become face-on within a few kpc radius. We superpose a Keplerian rotation curve by the thin line in figure 2, which corresponds to a point mass of $4.6 \times 10^9 M_{\odot}$. The dotted line indicates the rotation curve of a sphere whose surface density decreases exponentially with a scale radius of 0.5 kpc, which fits the observation fairly well. Thus, the rotation characteristics of M82 are quite different from those for other spiral galaxies, which are generally flat from the central few kpc to the outer disk (Rubin et al. 1982; Bosma 1981; Persic et al. 1996; Sofue 1996, 1997).

Figure 3 compares the rotation curve of M82 with those for the nearby Sb spiral M81 (Sofue 1997) and of our Galaxy (Honma, Sofue 1997), both of typical massive Sb type. In figure 3 we also compare it with those obtained for 37 nearby galaxies by thin lines (Sofue 1997). The rotation curve of M82 is indeed exceptional, because it has no flat part at all. It is more peculiar if it is compared with those of dwarf galaxies with similar masses such as NGC 4631, showing a gradually increasing rotation (e.g., Persic et al. 1996). We emphasize, however, that the steep nuclear rise and sharp maximum of the rotation curve at 200 pc radius resembles that for a central bulge of a massive galaxy like M81 or the Milky Way, whose centrally peaking component can be decomposed into a massive bulge.

Table 1. Potential parameters for M81 and M82.

Galaxy	Component	Mass M_i ($10^{11} M_{\odot}$)	Radius a_i^0 (kpc)
M81	Bulge	0.1	0.5
	Disk	1.1	7×0.5
	Halo	1.3	20
	Total............	2.5	
M82	Bulge	0.1	0.4
	Disk	1.0	5.0
	Total............	1.1	

3. Tidal Encounter and Truncation of a Disk

In an earlier paper (Sofue et al. 1992) we have shown that the Keplerian behavior of M82's rotation might be due to a truncation of an originally existing disk during a close encounter with M81. In order for the outer disk beyond 2 kpc to be truncated, we may assume that the tidal force of M81 was sufficiently strong even at a radius of $r = r_{\rm t} \sim 2$ kpc. Then the perigalactic distance between M82 and M81, R can be related to their mass and $r_{\rm t}$ through $(r_{\rm t}/R)^3 \sim M_{82}/M_{81}$, where M_{82} and M_{81} are the masses of the two galaxies. For $r_{\rm t} \sim 2$ kpc, $M_{82} \sim 5 \times 10^9 M_{\odot}$, and $M_{81} \sim 10^{11} M_{\odot}$, we obtain $R \sim$ 5 kpc.

In order to investigate how a tidal disruption of the outer disk has occurred we perform a simple simulation of the tidal encounter. We assume that a larger galaxy (M81) has a fixed potential similar to that of the Milky Way, which comprises a bulge, disk, and massive halo (table 1). The tidally disrupted galaxy (M82) is assumed to be represented by a single Plummer's potential.

The rotation axes of the two galaxies are taken to be parallel to each other, and are also parallel to the orbital angular momentum. Namely, the encounter occurs in the same galactic plane of the two galaxies in a direct sense.

The smaller galaxy's disk is represented by test particles, which are initially distributed in a rotating ring with a radius equal to the characteristic radius of the Plummer potential. Here, the potential is written in the form

$$\Phi = GM[r^2 + a(\sigma_r)^2]^{-1/2}, \quad (1)$$

where M is the mass of the disturbed galaxy, and the Plummer radius $a(\sigma_r)$ is proportional to the mean radius of the test particle distribution, defined by

$$a(\sigma_r) = a^0 \frac{\sigma_r}{\sigma_r^0}. \quad (2)$$

The mean radius σ_r of test particles around the center of M82 is given by

$$\sigma_r = \frac{\Sigma \Delta r_j}{N}, \quad (3)$$

where Δr_j is the spatial displacement of the j-th particle from the center of M82. Since the total mass is taken to be proportional to a^0, the initial peak velocity in the galaxy becomes constant (180 km s^{-1}) for any value of a^0. This modification of the Plummer's potential represents a semi-selfgravitating deformation of the disk. If the galactic disk is tidally distorted, the particle distribution becomes more dispersed, resulting in an increase of the disk radius, and, therefore, in a decrease of the centrifugal force within the disk. The present test-particle simulation might be too simple to be compared with the N-body self-gravitating simulations of a galaxy–galaxy interaction. However, the neglect of selfgravity would be not important in the present calculation, which aims at estimating the tidal disruption radius, because the tidal impact occurs within a time much shorter than the self-gravity regulating time scale, which is about several rotation periods.

We present an example of the calculations in figure 4. The smaller galaxy (M82) is put at 200 kpc away from the center of M81 with an impact parameter of 50 kpc and a velocity of 30 km s^{-1}. M81 orbits around M82 with peri- and apo-galactic distances of 3 and 220 kpc, respectively, in a period of 4 Gyr. If the Plummer radius is larger than 1.2 kpc, the disk of the smaller galaxy is almost totally disrupted during the close encounter, as represented by a sudden increase of the Plummer radius within $\sim$ 0.1 Gyr. On the other hand, if the Plummer radius is smaller than 1 kpc: the bulge is only disturbed, but the Plummer radius remains almost unchanged. In an actual bulge, however, since the stars' orbits would be more radial, we also examined counter-rotating cases, but obtained almost the same result. We also calculated

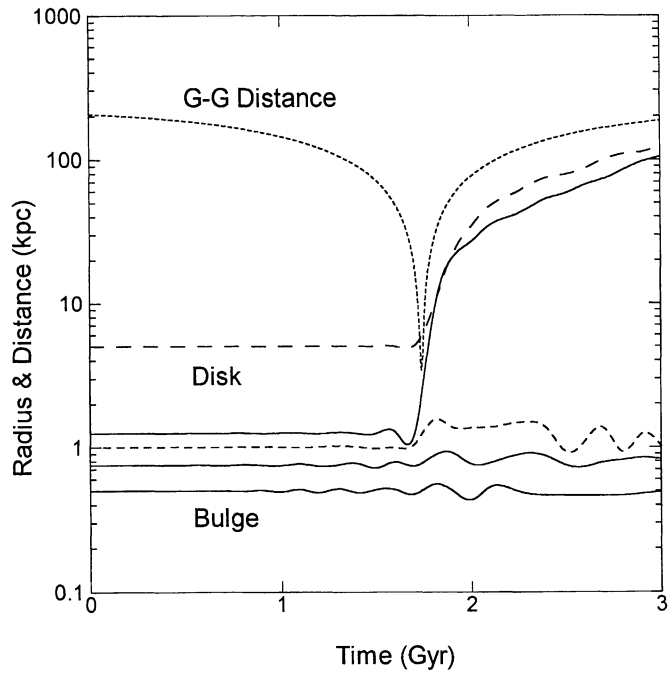

Fig. 4. Plot of the Plummer radius during a close encounter as a function of time. The galaxy is disrupted when the Plummer radius is larger than 1 kpc.

the same for a fixed Plummer radius, and obtained almost the same behavior as that of the radius of the test particle distribution mentioned above. By this simple simulation we have shown that M82's disk component is easily truncated during a close encounter, while the bulge can survive a tidal disruption.

We have analyzed and modeled the data based on the assumption of circular rotation for a first-order approximation. We have no means to analyze a higher-order motion, because the galaxy is edge-on. However, it is possible that the tidal interaction has caused a bar and non-circular motion (Noguchi 1988; Telesco et al. 1991; Yun et al. 1993). If such a bar is viewed side-on, the position–velocity diagram would behave more rigid-body like, manifesting the bar's pattern speed (e.g. Wada et al. 1994). This is, however, not the case in the observed data. If the bar is looked end-on, although this chance is small, a steeper rise and fall in the radial velocity than that expected from a circular motion would be superposed. In fact, if we look at the the rotation curve in figure 2 more carefully, it appears to decrease a little more rapidly than Keplerian, which might be due to a bar. Bar-related kinematics is beyond the scope of this paper. However, it would not affect the result of this paper, in which we discuss the lack of an outer flat-rotation disk.

4. Discussion

Evidence for a tidal interaction between M82 and M81 has been obtained. The two galaxies, together with NGC 3077 and NGC 2976, are embedded in a huge H I-gas envelope. The two galaxies are linked by an H I bridge, and a tidal tail extends from M81 toward the south (Gottesman, Weliachew 1977; Appleton et al. 1981; Yun et al. 1993). The molecular gas disk is also largely extended and distorted, extending toward the halo of M82 as high as ~ 1 kpc, and to the south (Olofsson, Rydbeck 1984; Young, Scoville 1984; Nakai et al 1987; Lo et al. 1987; Sofue et al. 1992). Moreover, the amount of molecular gas is extremely large, anomalous for the small total mass of M82, and is thought to be the cause of its intense starburst (Rieke et al. 1980; Telesco et al. 1991; Sofue 1988). On the other hand, M81 is known for its gas depression in the center (van der Hulst 1979; Sage, Westpfahl 1991).

We summarize a possible scenario for the M82–M81 interaction as follows. M82 was a larger and more massive spiral galaxy, containing H I gas in the outer disk and dense molecular gas in the central region. Through the close encounter with M81, when M82 penetrated the disk of M81, the outer disk of M82 was tidally truncated, but the bulge and nuclear disk have survived the tidal disruption. The truncated disk may have become the H I envelope and tails in the M81–M82 system. The central gas disk of M82 was dense enough, and ram-stripped the gas disk of M81 away, which was accumulated in the center of M82. This has caused the high-density molecular disk in M82, and a starburst. In contrast, M81 evolved into such a galaxy that contains little gas in the center.

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