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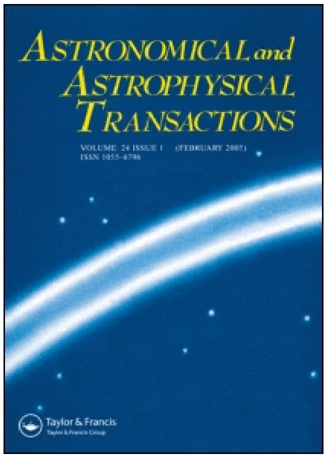

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TIDAL TAILS AND GALAXY EVOLUTION

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We review recent results on the tidal structures of spiral galaxies. Topics included are general characteristics of tails; kinematics of tidal structures and dark halos of host galaxies; and the frequency of tidal distortions at $z \sim 1$.

KEY WORDS Galaxies, photometry, spectroscopy, evolution

1 INTRODUCTION

Tidal features are very old known extragalactic objects. It is not generally realized that first remark about them was made more than 2 hundred years ago. William Herschel was the first to describe several double and multiple systems of faint nebulae and noted that some of the nebulae are connected by thin strips of luminous matter (see Eremeeva, 1966). Almost two hundred years later, Toomre and Toomre (1972) demonstrated by means of numerical modeling that such exotic and strange objects can be naturally explained as tidal distortions of gravitationally interacting galaxies.

Extended tidal structures are almost unexplored objects from both observational and theoretical points of view. We have now detailed information about 10 or 20 such structures only. In our report we shall discuss briefly the general observational characteristics of the tails and stress the importance of their investigation.

2 GENERAL CHARACTERISTICS OF TIDAL TAILS

1. *Local frequency.* The local fraction of tailed objects is about (1–2)% of all galaxies (Karachentsev, 1987; Reshetnikov, 2000). This estimate is obtained for relatively bright optical tails. While decreasing surface brightness level we shall observe an even larger fraction of tidal distortions. So tidal tails are rare but not extremely infrequent features.

2. *Spatial extent.* The typical sizes of tails are, on average, comparable with the sizes of host galaxies. But in some cases we observe huge structures – with lengths reaching hundreds of kiloparsecs (for instance, a 180 kpc (!) tail in Arp 299 – Hibbard and Yun, 1999).

3. *Surface brightness.* Known tidal features are generally very faint – with surface brightness levels in the B passband around 24^m–25^m (Schombert *et al.*, 1990; Reshetnikov, 1998).

4. *Total luminosity.* Surface brightnesses of the tails are low but they are very extended and, therefore, the total luminosity may be significant, with a mean value about a quarter of the luminosity of main galaxy (Schombert *et al.*, 1990).

5. *Optical colors.* Optical colors are, on average, bluer than those for the main galaxies. On the whole, the mean color indices are close to those for late-type spiral galaxies: $B - V \approx +0.5$ (Schombert *et al.*, 1990; Reshetnikov, 1998).

6. *m(HI), m(H_2)/m(HI).* Tidal tails are usually gas-rich structures with typical HI masses exceeding or equal to 10^9 solar masses (Hibbard and van Gorkom, 1996). In several cases the tails contain even mostly HI gas associated with the whole galaxy. Molecular gas (CO emission) was discovered recently in the tails of two interacting galaxies (Braine *et al.*, 2000). The mass ratio of the molecular gas to HI for those two tails is typical for late spirals.

Simple physics. To understand the development of tidal tails, one must recall how the water surface of the oceans get stretched radially by differential gravitational attraction exerted on it by our Moon. The differential forces between near and far side of the Earth depend on the third power of the Moon's distance from Earth. That is why the ocean's tides are rather mild. When two galaxies experience a close encounter with a perigalactic distance comparable to the galaxies' sizes, the tidal field of one galaxy stretches its neighbour radially and then the galaxies' rotation shears off stars and gaseous clouds from the outskirts of their parent galaxies. As a result, stars on the far side of each disk are ejected into long and thin tails.

The change of ith star momentum (Δv_i) during the encounter (Δt) can be expressed in terms of perigalactic distance and relative velocity $v_{\rm rel}$.

$$\Delta v_i = \frac{F_{\rm tid}}{m_i}\Delta t \propto \frac{1}{r_{\rm per}^3}\frac{r_{\rm per}}{v_{\rm rel}} \propto \frac{1}{r_{\rm per}^2 v_{\rm rel}}.$$

The additional energy may be sufficient to transfer the star from position r to position $r + \Delta r$

$$\frac{(\Delta v_i)^2}{2} = \varphi(r_i + \Delta r) - \varphi(r_i) \approx \left|\frac{d\varphi}{dr}\right| \Delta r,$$

where φ is the gravitational potential. Then the length of the tail can be estimated as

$$l_{\rm tail} \approx \Delta r \propto \left(r_{\rm per}^4\, v_{\rm rel}^2 \left|\frac{{\rm d}\varphi}{{\rm d}r}\right|\right)^{-1}. \qquad (1)$$

One can see from Eq. (1) that the extent of tidal tails depends strongly on resonances between the rotational and orbital motions (prograde encounters, in which the directions of the galaxies' rotation and orbital motion are the same – $v_{\rm rel}$ is small, – are most effective for tail building), on perigalactic distance and on the deepness of the common gravitational well.

And now we know some general things about tails, let's discuss why it is so interesting and important to study them. We shall discuss only three major points related to essential questions of galaxy evolution.

Star formation in an unusual environment. Tidal tails are very unusual settings for star formation. There are several groups of arguments in favour of ongoing star formation in some such features. For instance, they are gas-rich and have blue optical colors typical for late spirals and spiral arms. Bright blue star forming knots, often associated with HI condensations, are observed in several extended tails. For instance, we found a number of Hα condensations in the straight and long ($\sim$ 40 kpc) tail of NGC 4676 (The Mice) (Sotnikova and Reshetnikov, 1998). The characteristics of the condensations (linear sizes, optical and Hα luminosities) are common for giant HII complexes. The star formation rate in the tail estimated on the total Hα luminosity is typical for the disks of normal spirals ($10^{-9}M_\odot$ yr^{-1} pc^{-2}). Analytical estimates and numerical calculations indicate that the main star formation mechanism in the tidal tail of the Mice is large-scale gravitational instability in the gas of the tail.

Recent years' observational similarity of the brightest parts of tails and dwarf spiral galaxies have restored Zwicky's old idea that dwarf galaxies can be formed from the tidal material ejected during the interactions. And now this idea has become an interesting and actively growing field of study. For instance, as the interaction and merger rate was higher in the past, the production of such Tidal Galaxies might be very large. This mechanism can explain in part the excess of faint blue galaxies.

Tidal tails and dark halos. Another interesting field of work is the constraints on galactic dark halo characteristics following from the kinematics and morphology of tails. The extent of the tidal tail is very sensitive to the global dynamical structure of the interacting galaxies (Dubinski *et al.*, 1996, 1999) – it is difficult for long, massive tails to form in galaxy collisions in which the progenitors are surrounded by very large halos. As one can see from Eq. (1) the extent of the tail is inversely proportional to the deepness of the gravitational well, and tails extracted from disks might be unable to climb out of deep halo potential wells. But we observe very extended tails! It is suggested that this fact restricts the dark to luminous matter ratio in galaxies (Dubinski *et al.*, 1996).

Such a statistical approach has several evident limitations. In our work (Sotnikova and Reshetnikov, 1998) we proposed constraining dark halos through detailed modelling of specific interacting systems with good observational data about central galaxies and tails. We especially need good kinematical data for the tails but, unfortunately, such data are extremely poor now.

Probably, the best studied case is the well-known system The Mice. With the 6-m telescope we traced emission-lines rotation curve of the northern edge-on tail up to 40 kpc from the nucleus (Sotnikova and Reshetnikov, 1998). Using all available information about the central galaxies, we performed numerical modelling of the system. We found that the observed high radial velocities in the tail can be explained *only* if the system members possess rather massive dark halos – with a dark to luminous mass ratio within the region up to the tip of the tail of about 4.

Besides the Mice, we have the results of kinematical observations for several other objects with tails (work in progress).

Interaction rate evolution. Tidal deformations are clear indicators of recent gravitational perturbations of galaxies. Therefore, one can use their statistics to estimate the interaction rate in the past. It is very important because the rate of interactions and mergers at different redshifts depends on the model of the Universe, and on the details of galaxy formation models.

Tidal tails are faint structures. Due to cosmological dimming and K-correction, we can observe such distortions out to moderate redshifts only (1 or 1.5). Using the deepest currently available fields – North and South Hubble Deep Fields, – we selected 25 galaxies with probable tails at redshift between 0.5 and 1.5 (Reshetnikov, 2000). The general characteristics of the suspected tails are, on average, the same as in local interacting galaxies. We found that the volume density of galaxies with tidal tails changes with z as $(1 + z)^4$. Therefore, we estimated the rate of close encounters between galaxies of comparable mass leading to the formation of extended tidal structures. If this rate reflects the merger rate, our data support a steeply increasing merger rate at $z \sim 1$ and are consistent with current theoretical expectations.

Finally, we would like to stress that further detailed study and modelling of beautiful tidal features will be a powerful tool to investigate many important questions of extragalactic astronomy, such as star formation process, the mass and extent of galactic halos, interactions at high redshifts and so on.

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