Interactions and Mergers of Galaxies

S M Alladin and S N Hasan

When two galaxies approach each other, we can witness the effects of the tidal forces on a gigantic scale. Peculiar features like galactic bridges and galactic tails may form, or the two galaxies may even merge into each other and form a single system. Merger of two spiral galaxies leads to the formation of an elliptical galaxy. The interaction of gas during such galaxy encounters triggers star formation and activity of the nucleus. It is generally being accepted that galaxy interactions and mergers play a vital role in galactic evolution.

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Introduction

Galaxies are large aggregates of matter containing about a hundred billion stars. Most of them have regular shapes and can be broadly classified into two main categories: ellipticals and spirals. The former are elliptical in shape while the latter consist of a central bulge, a disk and a halo. The distribution of matter in the disk exhibits a spiral structure. The motion of the stars is predominantly random in an elliptical galaxy and nearly circular coplanar in the disks of spiral galaxies.

In the early 1920's a subject of vigorous controversy in astronomy was whether there existed galaxies other than our own. A historical debate took place between Heber D Curtis and Harlow Shapley in which Curtis felt that some of the nebulae were external galaxies while Shapley argued that all nebulae were parts of our galaxy. The observations at that time were inadequate for a definite conclusion to be drawn. The controversy was finally settled in 1924 when Hubble resolved the outer parts of the Andromeda nebula into stars. It was then realized

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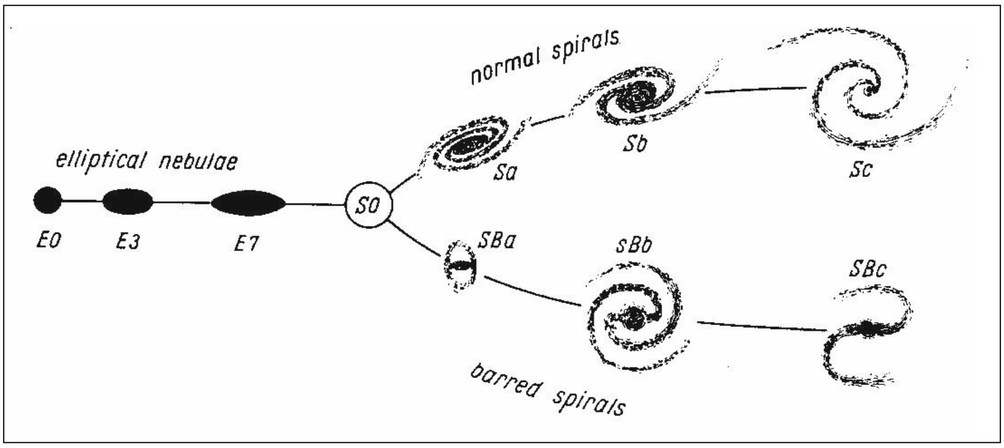

Figure 1. The Hubble tuning fork diagram.
Courtesy: NASA/STScI

that there are also other galaxies in the universe. We now know that there are billions of galaxies.

Hubble's classification of galaxies is well known (*Figure* 1). Hubble classified galaxies into ellipticals, spirals and irregulars. Ellipticals were further classified into E0–E7 in increasing order of flatness, and spirals into normal and barred spirals, each of which was further subdivided into types a, b, c in increasing order of importance of the spiral arms in relation to the nucleus. The disk-like S0 galaxies or lenticulars mark the transition between ellipticals and spirals. The ellipticals range from small dwarf ellipticals of 10^8 M_{Sun}(mass of the Sun $M_{Sun} \approx 2 \times 10^{33}$g) to massive super giant galaxies of mass 10^{12} M_{Sun}. The spirals have considerably smaller variation in mass.

Our galaxy, known as the Milky Way, is a spiral galaxy. The Sun revolves around the galactic centre at a distance of about 10 kiloparsecs (1 parsec = 3×10^{18}cm) in a nearly circular, coplanar orbit completing one revolution in 2×10^8 years. The diameter of the disk of stars and gas is about 30 kiloparsecs. The halo also contains a large amount of dark matter which cannot be observed by electromagnetic radiation but can be inferred from its gravitational effects. The centre of our galaxy contains a black hole of mass more than 3×10^6 M_{Sun}.

Many of the galaxies are members of groups and clusters. In groups and clusters, galaxies move in all directions. In the course of its motion, a galaxy may come too close to another and even interpenetrate it. Stars in a galaxy are separated from one another by distances which are very large compared to their dimensions. Hence the probability of two stars undergoing a head-on collision with each other is exceedingly small, even in cases of penetrating collisions of galaxies.

Galactic Bridges and Tails

According to Newton's law of gravitation, two bodies attract each other by a force which varies as the product of their masses and inverse square of their separation distance. When the two bodies are very close to each other, the variation of this force over the spatial extent of the body, which varies as the inverse cube of the distance, can be very important. This is best illustrated by the formation of tides in the oceans of the Earth. Tides occur in the oceans because of the difference in gravitational force between the centre of the Earth and its surface. The Sun is about 3,30,000 times more massive than the Earth while the Moon is 81 times smaller in mass than the Earth. The Sun's distance from the Earth is about 400 times greater than the Moon's distance. Hence (Mass)/(Distance)^3 for the Sun is less than that for the Moon by a factor of 2. Therefore the Moon, because of its proximity, turns out to be more powerful than the Sun in raising tides in the ocean. An important feature of the effect of the tidal force is that tides are raised not only on the side of the Earth facing the Moon but also on the opposite side of the Earth.

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When galaxies come close to one another we observe that tidal forces are in action on a gigantic scale. The orbits of stars in the outer parts of the galaxies are greatly perturbed. This leads to the formation of a bewildering variety of morphological features in galaxies. Sometimes

Figure 2 (left). The Antennae (NGC 4038/4039) .
Courtesy: NASA/STScI
Figure 3 (right). Whirlpool Nebula (M51/NGC 5195).
Courtesy: NASA/STScI

two galaxies are connected by a luminous bridge, sometimes tails stream out from the galaxies from the side away from the companion.

Atlas of Peculiar Galaxies by Vorontsov-Velyaminov (1959) and Arp (1966) are well known. The Antennae (NGC 4038/4039) (*Figure* 2) and the Whirlpool Nebula (M51/NGC 5195) (*Figure* 3) are famous examples of interacting galaxies.

In 1972, Alan Toomre and Juri Toomre showed that tidal interaction between galaxies could indeed produce features such as tails and bridges. Striking bridges and tails can be produced if the following conditions are satisfied:

1. The two galaxies should approach each other in nearly parabolic or highly eccentric elliptic orbits. In a fast hyperbolic encounter, the encounter time is small and hence the tidal force does not get sufficient time to make appreciable structural change in the galaxies.
2. The relative motion of the galaxies should be in the same sense as that of the revolution of the stars in the galaxies since this will increase the time of tidal interaction.
3. The galaxies must penetrate each other but not too deeply.

Head-on collisions of galaxies do not lead to the formation of bridges and tails. Such collisions however convert a spiral galaxy into a ring galaxy. Many ring galaxies have been discovered with a companion close by. The Cartwheel Galaxy (*Figure* 4) is an example of a ring galaxy.

Figure 4.Cartwheel galaxy.
Courtesy: NASA/STScI

Changes in Energies of Galaxies in Galactic Encounters

A study of the motion of stars in galactic encounters is essentially an N-body problem where N is of the order of 10^{11}. During the encounter, a star gains or loses energy depending upon its position and velocity in the galaxy. Those stars which gain energy move outward and those which lose energy move inward towards the galactic centre. What happens to the galaxy as a whole depends upon the cumulative effects of all its stars. N-body simulations of galactic encounters have been extensively performed with modern computers.

Some valuable insight into the basic physics can however be obtained analytically by estimating the velocity changes by integrating the tidal acceleration over time under the assumption called the 'Impulse Approximation'. It was first used by Spitzer in 1958 to estimate the energy change of a galactic star cluster due to the tidal effects of interstellar clouds.

Consider a galaxy of mass M_1 encountering a galaxy of mass M and let m be the mass of a star in M. Suppose the galaxies do not penetrate each other during their motion. The star of mass m may be considered as forming a binary with the galaxy of mass M. Here $m << M$. The energy transfer from the orbital motion of the galaxy to the motion of the constituent stars will depend upon the cumulative effect of all the binary-single body encounters.

A head-on collision converts a spiral galaxy into a ring galaxy.

Let $\vec{v}_i$ and $\vec{v}_f$ be the initial and final velocities of a star of mass m in the parent galaxy of mass M. Let $\vec{v}_f = \vec{v}_i + \Delta\vec{v}_i$ where $\Delta\vec{v}_i$ is the change in velocity of the star in the galactic encounter due to the tidal effect of M_1. Thus the change in kinetic energy of the star during the encounter is given by

$$\frac{1}{2}m(\vec{v}_f^2 - \vec{v}_i^2) = \frac{1}{2}m\left[\vec{v}_i^2 + 2\vec{v}_i.\Delta\vec{v}_i + (\Delta\vec{v}_i)^2 - \vec{v}_i^2\right]$$
$$= \frac{1}{2}m\left[2\vec{v}_i\Delta\vec{v}_i + (\Delta\vec{v}_i)^2\right].$$

The first term on the right hand side will generally be much larger than the second term. The change in the velocity of an individual star will therefore be chiefly governed by the first term. But the first term can be positive or negative. If $\vec{v}_i$ and $\Delta\vec{v}_i$ are uncorrelated its average value would be zero. The second term, though much smaller than the first term, is always positive. Hence it will add up for all the stars, with the result that **the total kinetic energy, $\boldsymbol{T}$, of the galaxy will increase during the encounter**. In the impulse approximation, we assume that the relative velocity of the galaxies is large compared to the stellar velocity, and hence we neglect the change in the potential energy Ω. Hence the change in the total energy of the galaxy

$$\Delta U = \Delta T = \frac{1}{2}\sum m_i(\Delta\vec{v}_i)^2,$$

where the summation is over all the stars in the galaxy.

For a stable galaxy, we obtain from Virial Theorem (see *Box* 1)

$$U = \frac{\Omega}{2} = -\frac{GM^2}{4\bar{R}},$$

where $\bar{R}$ is the dynamical radius.

We assume $\bar{R} \approx R_{rms}$, where R_{rms} is the root mean square radius of the parent galaxy of mass M. For a stable galaxy, the total energy U is negative. The ratio $\Delta U/|U|$ provides a convenient estimate of the intensity of the disruptive effects of the tidal force. If

Box 1. The Energy of a Stellar System

Consider a stellar system, such as a galaxy of mass M containing N stars each of mass m_i.

It's total kinetic energy is given by

$$T = \frac{1}{2}\sum_{i=1}^{N} m_i v_i^2 = \frac{1}{2} M\sigma^2, \tag{a}$$

where v_i is the magnitude of the velocity of star of mass m_i and σ is the magnitude of the root-mean-square velocity, i.e. σ^2 is the average of v_i^2.

The potential energy of the system is given by

$$\Omega = -\sum_{pairs\ i,j} \frac{Gm_i m_j}{r_{ij}}, \tag{b}$$

where r_{ij} is the distance between m_i and m_j and the summation is over all the pairs. If m is the average mass of a star, then

$$\Omega = -Gm^2 \sum_{pairs\ i,j} \frac{1}{r_{ij}}. \tag{c}$$

The total number of pairs is $(1/2)\ N(N-1)$. Since N is very large, this gives $N^2/2$. Therefore

$$\Omega = -\frac{Gm^2N^2}{2}\left\langle \frac{1}{r_{ij}} \right\rangle. \tag{d}$$

We denote the average $\langle 1/r_{ij} \rangle$ by $\langle 1/\bar{R} \rangle$ where $\bar{R}$ is called the dynamical radius. Also $M^2 = m^2N^2$. Hence

$$\Omega = -\frac{GM^2}{2\bar{R}}. \tag{e}$$

For stability, the potential energy should exceed the kinetic energy. Hence the total energy U of the system should be negative.

If the system is not only stable but is also in a steady state, the Virial Theorem should be satisfied, that is

$$2T + \Omega = 0. \tag{f}$$

Since the total energy $U = T + \Omega$, it follows that for a stellar system in a steady state

$$U = -\frac{\Omega}{2} = -\frac{GM^2}{4\bar{R}}. \tag{g}$$

It also follows from equations (a), (e) and (g) that for a stellar system in a steady state

$$\sigma^2 = \frac{GM}{2\bar{R}}. \tag{h}$$

Box 2.

Consider the impulse given to a member star in the galaxy of mass M by the approaching galaxy of mass M_1. One estimates that the change in its velocity is approximately

$$\Delta v \sim f\frac{GM_1}{p^2}\cdot\Delta t \sim f\frac{GM_1}{p^2}\cdot\frac{R_{rms}}{V},$$

where p and V are the distance and velocity at closest approach, and Δt is the approximate duration of the gravitational interaction between the galaxies. Here, f is a constant that takes into account the detailed geometry of interaction.

The change in the kinetic energy of the galaxy of mass M is approximately

$$\Delta KE \sim \frac{f}{2}M\left(\frac{GM_1}{p^2}\cdot\frac{R_{rms}}{V}\right)^2 \sim \Delta U.$$

So, the ratio

$$\frac{\Delta U}{U} \sim \frac{2fGM_1^2}{Mp^4}\cdot\frac{R_{rms}^3}{V^2}.$$

Detailed calculations give $f \sim 8/3$ which yields the result mentioned in the text.

$\Delta U/|U| > 1$, U will become positive after the encounter, and hence the galaxy will not be stable. For a fast non-interpenetrating encounter it can be shown that (see *Box* 2)

$$\frac{\Delta U}{U} = \frac{16}{3}\frac{GM_1^2}{M}\frac{R_{rms}^3}{p^4V^2},$$

where p and V are the distance and velocity at closest approach and G is the constant of gravitation.

This shows that the disruptive effects are not large for large 'p', or grazing collisions. Head-on collisions, with small values of 'p', can however lead to large disruptive effects.

Galaxy Mergers

Since the energy of the stellar content of both the galaxies increases during the encounter, it follows from the law of conservation of energy that the energy E of the orbital motion of the two galaxies decreases during the encounter. Thus an initial hyperbolic orbit of a pair of galaxies can be converted into a bound orbit. Further, tidal action will decrease the separation of the two galaxies and lead to their merger.

From the law of conservation of energy

$$|\Delta E| = \Delta U + \Delta U_1.$$

$|\Delta E|/E > 1$ gives the criterion for tidal capture and subsequent merger, where $E = \frac{1}{2}\left(\frac{MM_1}{M+M_1}\right)V^2$, V being the initial velocity in a hyperbolic encounter. If we denote by V_{cap} the initial velocity below which the two galaxies would merge, then

$$\frac{1}{2}\frac{MM_1}{M+M_1}V_{cap}^2 = \Delta U + \Delta U_1.$$

For identical galaxies one obtains from detailed calculations, $V_{cap} = 0.64\sigma$ for a grazing collision and $V_{cap} = 2.35\sigma$ for a head-on collision, where σ is the root-mean-square velocity of a star in a galaxy.

The advent of large computers has enabled us to calculate the merger time of interacting galaxies. These calculations have shown the vehemence of the tidal effects. Typical interacting galaxies merge in time of the order of $10^8 - 10^9$ years. The merger remnants are bigger in size than the initial galaxies but the merging process is not homologous. It results in a final collapsed object having a higher central concentration and a more extensive envelope than its progenitors. Head-on collisions of initially spherical galaxies lead to prolate merger remnants elongated along the direction of motion, while off centre collisions lead to oblate remnants flattened along the initial orbital plane. For intermediate collisions the shapes are triaxial.

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Computer studies have also demonstrated that the merger of two disk (spiral) galaxies leads to the formation

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of an elliptical galaxy. A number of elliptical galaxies have also been discovered whose observed properties indicate that they have been formed by the merger of spiral galaxies. This discovery is of great importance in galactic evolution since it shows that the morphology of a galaxy can be drastically altered in the merger process.

Many elliptical galaxies with shell-like features have also been discovered. These have been interpreted to have formed when a small spiral galaxy collides with a giant elliptical galaxy. In such a collision the spiral galaxy loses its identity and its stars are scattered in the gravitational field of the elliptical galaxy in the form of shells.

Dense clusters of galaxies often contain a huge galaxy at their centre. It has multiple nuclei and a highly extended envelope. Such a galaxy is formed when galaxies in a compact group of galaxies undergo mergers and the group of galaxies evolves into a single big galaxy.

Galaxy Interactions in Our Neighbourhood

Our galaxy, the Milky Way, is a member of the Local Group of galaxies containing about 30 members in a volume of radius about 1 mega parsec. The Andromeda galaxy (M31) and our Galaxy are the most luminous and biggest members. They are separated by a distance of about 700 kiloparsecs. Each of these is surrounded by less massive galaxies many of which are dwarf ellipticals.

Our closest neighbours are the Large Magellanic Cloud and the Small Magellanic Cloud at a distance of about 50 kiloparsecs. Intergalactic filaments connect the two Magellanic Clouds. The tidal interaction between our galaxy and the Magellanic Clouds has led to the formation of a long gaseous stream known as the Magellanic Stream. It extends from the Magellanic Clouds to the South Galactic Pole and beyond covering an arc of 180^o in the sky. It forms a ring in the plane perpendicular to the disk of our galaxy. Several small galaxies lie in this plane. It appears that these small galaxies owe their origin to the same tidal interaction that produced the Magellanic Stream. The intensity of the tidal interactions suggests that the mass of our galaxy is much more than what we can infer from the luminous matter. Thus, a great deal of matter of our galaxy is in the form of dark matter. Various tidal models have been proposed to explain the Magellanic Stream.

We can envisage the future of our galaxy through interaction with its neighbours as follows. Energy transfer from orbital to stellar motions will make the satellite galaxies come closer to their primaries. In time of the order of 10^9 years, our Galaxy and M31 would have gobbled their neighbours. M31 is approaching our galaxy with a speed of about 100 km/sec. In less than 10^{10} years the merger of our galaxy with M31 will take place. The entire Local Group will then become a single large elliptical galaxy.

Role of Gas in Galaxy Interactions

In many interacting galaxies about 10% of the luminous mass is in the form of gas. This interstellar gas is more sensitive to tidal perturbations than the stars, and in close galactic encounters violent shocks can develop in the gas. These shocks can dissipate much of the energy of the gas with the result that the gas falls towards the galactic centre. A study of interacting galaxies indicates that the infall of gas triggers star formation. The most infrared-luminous galaxies appear to be starbursts triggered by merger of two galaxies.

Our galaxy has a massive black hole at its centre and it appears that many other galaxies also contain massive black holes at their centres. When the infalling gas spirals into the black hole in a galactic encounter, it grows extremely hot and radiates powerfully before it vanishes from sight and goes into the black hole. This produces

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Box 3. Seyfert Galaxies, Radio Galaxies and Quasars

Seyfert galaxies are spiral galaxies with unusually bright, tiny cores that fluctuate in brightness. They do not have radio lobes. Most are powerful sources of infrared radiation. In addition, some emit intensely in the radio, X-ray, and gamma ray regimes. Approximately 2% of all spiral galaxies are Seyfert galaxies. This means either that about 2% of all spiral galaxies have active core or that most spiral galaxies have potentially active cores which erupt 2% of the time.

Radio galaxies are usually elliptical and are very luminous at radio wavelengths (up to 10^{38} W between 10 MHz and 100 GHz). The radio emission is due to the synchrotron process. They often exhibit jet structure from a compact nucleus. They typically exhibit two lobes of radio frequency emission that are often approximately aligned with the jets observed in the visible spectrum and that may extend for millions of light years. The observed structure in radio emission is explained by the interaction between twin jets and the external medium.

Quasar (acronym of QUASi-stellAR radio source) is an astronomical source of electromagnetic energy, including light, which outshines the energy output of the brightest stars. A quasar releases energy equal to the combined output of hundreds of average galaxies. In optical telescopes, a quasar looks like a star (i.e. it is a point source) with a high redshift. The general consensus is that this high redshift is cosmological, the result of Hubble's law, which implies that quasars must be very distant and hence very luminous. The highest redshift (for redshift, see *Box* 4) currently known for a quasar is 6.4.

The scientific consensus is that quasars are powered by accretion of material onto supermassive black holes in the nuclei of distant galaxies, making these luminous versions of the general class of objects known as 'active galaxies'.

the activity of the galactic nucleus. This inference is supported by the observation that many active galaxies (such as Seyfert galaxies, radio galaxies and quasars, see *Box* 3) have interacting galaxies as their companions.

Evolution of Galaxies

In 1929, Hubble discovered that clusters of galaxies are receding from each other and greater their separation, greater is their recession. This is inferred from the redshifts of the spectral lines (see *Box* 4). This discovery is of seminal importance in cosmology. It also follows from this discovery that in the early universe clusters of galaxies were closer to one another.

Box 4. Redshift and the Hubble's Law

Redshift is defined as the change in the wavelength of the light divided by the rest wavelength of the light, as

$$z = \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}},$$

where λ_{em} is wavelength of emitted photon and λ_{obs} is wavelength of observed photon.

Hubble's Law states that the redshift in light coming from distant galaxies is proportional to their distance from the observer. The law was first formulated by Edwin Hubble and Milton Humason in 1929 from observations. They observed that distant galaxies were receding at velocities directly proportional to their distance d,

$$v = H d,$$

where H is the constant of proportionality known as Hubble's constant.

The fact that more distant objects are receding more rapidly than closer ones is interpreted as implying expansion of the universe, and is the main observation which led to the Big Bang theory. The age of the universe is of the order of H^{-1} (which is expressed in units of time).

According to current models of the universe, the WMAP (Wilkinson Microwave Anisotropy Probe) data released in March 2006 shows that the current value of the Hubble constant, H_0 is 70 (km/s)/Mpc (1 Mpc $= 10^6$ parsec), $+2.4/-3.2$. Taking into account other considerations, this implies that the age of universe is 13.7 billion ± 200 million years.

With the Hubble Space Telescope we are now able to observe collisions between galaxies and even collisions between clusters of galaxies that occurred in the early universe. We find that there is a much larger percentage of irregulars, peculiar and interacting galaxies at large redshifts (see *Box* 4), and ellipticals are fewer. The galaxies at larger redshifts are also small in size. Thus it is being increasingly realized that galaxy collisions may have played a prominent role in galactic evolution. The present evidence suggests that the Hubble sequence (*Figure* 1) is a sequence of decreasing merger effects.

Conclusion

The study of galaxy interactions reveals the far-reaching effects of the tidal force. The familiar tidal force exerted by the Moon and the Sun which raises tides in the waters of the oceans of the Earth is also responsible for converting normal galaxies into various peculiar galaxies and in producing galaxy mergers on a vast scale. It has played an important role in the formation and evolution of galaxies in the past.

Suggested Reading

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Errata

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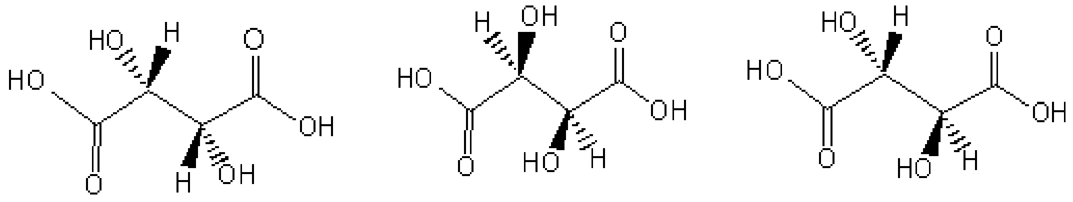
Page 44: In the article, Pastuer – the Harbinger of Stereochemistry, the correct *Figure* 2 is reproduced here.



(+)-Tartaric acid
d-Tartaric aicd
L-Tartaric acid
(*R,R*)-(+)-Tartaric acid
m.p 168-170 °C

(-)-Tartaric acid
l-Tartaric acid
D-Tartaric acid
(*S,S*)-(-)-Tartaric acid
m.p. 168-170 °C

meso-Tarataric acid
(R,S)-Tartaric acid
m.p. 140 °C

d,l-Tartaric acid, m.p. 210 °C

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