emitting debris from the radio galaxy 3C129 (1972); comparison of the optical and HI spiral structure of M101 (1973); a map of a radio galaxy -NGC1265- showing the whole story from ejection of blobs to formation of diffuse tails (1973); discovery of the giant radio galaxies DA240 and 3C236 with megaparsec sizes (1974); measurement of the radial velocity field of M81 spectacularly confirming the predictions of the density wave theory (1974) (Figure 4); tests of general relativistic light bending close to the Sun (1975); a map of the galactic centre showing Sgr. A East & West (1975); observations of a galactic warp in NGC5097 similar to that suspected in our own galaxy (1976); a map of the continuum halo of the edge-on galaxy NGC 4631 (1977); radial velocity fields of 22 spiral galaxies (1978); a measurement of the *expansion* of Tycho's supernova in the eight years from 1971 to 1979; and maps of the hydrogen recombination line emission (1980).

There was no competition for WSRT in the decade mentioned above. The Very Large Array (VLA) in the USA came on line in 1980, and since then has had the No. 1 place amongst radio telescopes of the world. But I would like to point out that WSRT has continued to be useful and important and can still do some things better than the VLA. Also, the VLA benefitted immensely from the experience of WSRT in many ways, not least because both the first and present directors of the VLA came after years at WSRT. Oort followed everything that the VLA did as if it was his 4th telescope, and his views have greatly influenced even the development of GMRT in India, which at meter wavelengths will hopefully be to the nineties what the VLA was to the eighties and WSRT to the seventies.

I have already described Oort's reactions to Reber's work which showed his *instant* ability to recognize what would become of great importance in due course. Another example is a description in his own words: '... the epic of the first successful descent into the past of the Universe which was made by Ryle and coworkers at the Cavendish Laboratory. Radio astronomy clearly promised to become the *tool par excellence* for studying the universe'[4]. His mind remaining so much younger than his body, Oort had no difficulty in becoming an observational radio astronomer after 50 and pushing for the creation of new and bigger and better radio telescopes. In my view he contributed as much or more to the development of radio astronomy as any of the great telescope-building pioneers who came in from a different world, i.e. one where a great deal was known about radio but little or nothing about astronomy. It was only in Holland and only because of Oort that 'an astronomer from the start determined the observing programmes, the technical priorities and the next telescope's configuration'[5]. He knew what he was doing, so it is no wonder that the rest of us owe so much to him.

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Galactic rotation

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The discovery of galactic rotation—both, the global rotation and the local differential rotation in our Galaxy, will be discussed here. Oort made seminal contributions to this topic. A brief historical background is given first so as to place Oort's contribution in the proper perspective. This is important since the topic of galactic rotation was crucial in confirming the correct nature of our Galaxy.

Background

As late as 1920s, the nature of our Galaxy was not well-established[1-3]. There were two rival pictures for our Galaxy. One was the Kapteyn model based on the method of star counting. In this picture, the Sun lies at the centre of the Galaxy which has a roughly flattened ellipsoidal shape with planar and perpendicular sizes of about 2.8 kpc and 0.6 kpc respectively, corresponding to about 10% of the central density. In this picture, the other spiral nebulae were believed to be spiral galaxies similar to our Galaxy.

In sharp contrast to this was the picture of our Galaxy by Shapley, based on the distance measurements using the period-luminosity relation for RR Lyrae variable stars in the globular clusters. From the observed period of a RR Lyra variable, its absolute luminosity is known and comparing this to the observed value, the distance to the star can be determined. Shapley found that the globular cluster distribution was concentrated towards a narrow range of galactic longitudes, and was centred around a point about 13 kpc away from the Sun. Shapley boldly argued that since the globular clusters are massive objects, each with a mass of $\sim 10^5 M_{\odot}$, they must be distributed symmetrically with respect to the dynamical centre of the Galaxy. Therefore, the Sun lies not at the centre of the Galaxy but rather out in the disk $\sim$ 13 kpc away from the galactic centre, and the overall size of the Galaxy is $\sim$ 50 kpc—which is much greater than the size of the Kapteyn Universe. Shapley also argued (based on Van Maanen's proper motion measurements) that other spiral nebulae were a part of our Galaxy.

(The discrepancy between the two pictures was later recognized to be due to the neglect of obscuration by the interstellar medium (ISM) which affects the tracers in Kapteyn picture much more since these were disk stars whereas Shapley was lucky in his choice of tracers which were mostly in a halo. Thus Shapley got a qualitatively correct picture—only his distance scale is off by a factor of $\sim$2, whereas Kapteyn got a grossly wrong picture. Kapteyn had, in fact, been unhappy about the heliocentric flavour of his model. But despite his search for the absorption and reddening effects due to the ISM, they were not detected. The existence of ISM was conclusively proven by Trumpler's study of sizes of open clusters later in 1930.)

This then led to the famous 'Great Debate in Astronomy' between Curtis and Shapley (in 1920) where these views on the size of our Galaxy and the nature of and distances to other spiral nebulae were discussed and while no conclusion could be reached, the community at least became aware of the various important issues involved[1-3].

The nature of spiral nebulae was established by Hubble from his studies of Cepheid variables in Andromeda (M31) and M33. Cepheids are intrinsically brighter variables and hence could be used to study farther distances. Hubble found that M31 and M33 were at a distance of about 300 kpc from the Sun. This was much bigger than even the large size advocated by Shapley and thus it was established that spiral nebulae are large systems similar to our Galaxy and that they lie external to our Galaxy.

The nature of our Galaxy was explained around the same time by the study of its kinematics and dynamics. This line of study was started by Lindblad[4] who proposed that our Galaxy consisted of several subsystems of the same total extent, each rotating uniformly w.r.t. the galactic centre with a uniform speed (far greater than the random motion). The higher the rotation, and the smaller the random motion in a subsystem, the flatter it is. Thus Lindblad could qualitatively explain the observed phenomenon of lagging of high velocity stars. Lindblad also argued that the Kapteyn model gives too small an escape velocity and hence the Galaxy will not be able to hold onto the globular clusters which have a high random velocity. Since these are massive objects, these probably cannot form readily. This was another argument against the Kapteyn model.

Differential rotation in the Galaxy

Oort[5] confirmed and extended the overall rotation model of Lindblad. Oort presented a general kinematical model of differential rotation for the Galaxy. He considered the general case when the stars are in a dynamical equilibrium, and the stars of various random velocity dispersions at a given radius rotate with a single velocity w.r.t. the galactic centre. This is set by the overall gravitational force of the Galaxy. He did not consider the somewhat artificial concept of subsystems used by Lindblad. Oort considered the Galaxy to be in a non-uniform or a differential rotation—namely, the regions closer to the galactic centre rotate faster. This is a general property of any gravitating system, since energy is minimized if there is a central concentration of mass—the latter leads to a differential rotation. A constant density distribution, on the other hand, would yield a solid body rotation—this is in fact now seen at the very central few kpc region in galaxies.

Oort wrote down the general rotation law in the galactic plane for a differentially rotating disk, and showed that the results from this agree with the observational data on local stellar kinematics. Let R_0, $\Theta(R_0)$, and $\Omega = \Theta(R_0)/R_0$ denote the galactocentric distance, the rotation velocity, and the angular speed of rotation respectively of the solar neighbourhood region. Let v_r, and v_t denote the radial and transverse velocity respectively, of an object at a distance d from the Sun ($d \ll R_0$) and located along the galactic longitude l. The local values of v_r and v_t arising purely due to the differential rotation in the Galaxy were obtained by Oort[5] to be:

$$v_r = A\, d \sin 2l, \tag{1}$$

$$v_t = d\,(A \cos 2l + B), \tag{2}$$

where A and B are local constants and are defined by

$$A = \frac{1}{2}\left[\frac{\Theta_0}{r_0} - \left(\frac{d\Theta}{dR}\right)_0\right] = -\frac{1}{2} R_0 \left(\frac{d\Omega}{dR}\right)_0 \tag{3}$$

$$B = -\frac{1}{2}\left[\frac{\Theta_0}{r_0} + \left(\frac{d\Theta}{dR}\right)_0\right] = -\frac{1}{2}R_0\left(\frac{d\Omega}{dR}\right)_0 - \Omega_0. \quad (4)$$

These local constants are now known as Oort constants. A and B have units of km s^{-1} kpc^{-1}. A is an indicator of the local shear in the galactic disk, and B is an indicator of local vorticity.

Oort considered available observational data for velocities of various groups of stars (such as O–B type stars, Cepheids and so on) and showed that in each case the radial velocity over distance (v_r/d) showed the *double* sine-wave dependence on l, the longitude, as given by eq. (1) where l was measured from the direction towards the centre of the globular cluster distribution as given by Shapley. This was clear evidence for Shapley's model.

The relation in eq. (2) is harder to check because it requires measurements for transverse or proper motions. There motions are small and hence are notoriously hard to obtain, often requiring up to 30–50 years for the cumulative stellar motion to stand out above the standard errors. This measurement is also plagued with large systematic errors that are hard to get rid of. Oort[6] did not use eq. (2) to obtain a value for B. He noted, however, that the relation for the transverse velocities [eq. (2)] could match the observations if in addition to the central $1/R^2$ force term a force term proportional to R were included. (The radial velocities on the other hand could be fitted by a pure $1/R^2$ force law.) This implied that the finite extent of the galactic (disk) mass distribution had to be taken into account. This was the first quantitative estimate of the relative amount of mass in the disk versus that in the central regions. The constants A and B still remain the best constraints for the more sophisticated galactic mass models[7].

Thus Oort's work established the concept of differential rotation in the Galaxy. It also confirmed the Shapley model of the Galaxy—namely that the Galaxy is a large, differentially rotating disk system and the Sun lies far away from the galactic centre, out in the disk. Even after 65 years, this paper is relevant, and contains the clearest description of the subject of galactic rotation where the basic physical issues are presented with great clarity of thought, and it deserves to be read by anyone studying galaxies.

Oort had been aware of Lindblad's work and in fact his first paper on galactic rotation[5] is titled 'Observational evidence confirming Lindblad's hypothesis of a rotation of the galactic model'. Bok[6] has told an interesting story about how Oort arrived at this picture. Oort was giving seminars about the rotation model of Lindblad every Monday afternoon at Leiden. Then one Monday he announced that he had got involved in the complex mathematics of this model and there would be no lecture next week, and there were no seminars for the next two Mondays. The third Monday after the crisis, Oort gave a talk where he clearly presented his simple physical model of differential rotation, and the observational implications including the detection of the double sine-wave dependence of radial velocity, and the difficulty of measuring B via proper motions.

Oort's model of galactic differential rotation is simple (like many important discoveries are—especially in retrospect) and the model involves simple algebra but it had profound and far-reaching implications in explaining the very nature of the Galaxy and its dynamics. This problem exemplifies Oort's approach. Oort recognized that this was an important problem. He came up with an intuitive, physical picture which simplified the whole problem at a stroke. This was then backed by methodical, painstaking work of comparing the observations with the results from his model. In fact the observations of stellar motions were used as a guideline in setting up the rotation model.

Oort then worked out some important dynamical consequences of his model of differential rotation[8]. These include the explanation of the observed lag of the high velocity stars w.r.t. the dynamical local standard of rest, and the observed ellipsoidal distribution of the random motions of stars. Oort started with a steady-state description as given by a collisionless Boltzmann equation. He then solved this rigorous stellar dynamics problem and explained the lag of high velocity stars or the asymmetric drift in terms of the radially decreasing density gradient in the Galaxy. Starting from the collisionless Boltzmann equation, Oort also showed that the ratio of the average random radial velocity square to the average random azimuthal velocity square (which decides the shape of the velocity ellipsoid) can be given in terms of the constants A, B to be:

$$\frac{\langle v_r^2 \rangle}{\langle v_\theta^2 \rangle} = \frac{(A-B)}{-B} = \frac{4\Omega_0^2}{\kappa^2}. \quad (5)$$

An identical result was obtained for small random motions by Lindblad[9], using the idea of epicyclic motions of stars—that is by treating the stellar motions as a first order perturbation problem. This ratio agrees with the observed values.

Values of the Oort constants A and B

Because of the importance of the Oort constants A and B for the study of the rotation and dynamics of the Galaxy, a lot of work over the years has been devoted to their accurate determination. The best method for the determination of A still remains the study of variation of radial velocity of objects as a function of their distance d—see eq. (1). Another method involving larger errors, is by studying proper motions and using the relation in eq. (2). The only direct way to obtain B is via the study of proper motions—the observations for which are frought with errors as discussed above. An indirect way is to use the observed velocity ellipsoid, and given A, obtain B from eq. (5). Also note that

$$A-B=\Omega, [(\mathrm{d}\Theta)/(\mathrm{d}R)]_0=-(A+B). \quad (6)$$

Thus R_0, Θ_0, A, B form an internally consistent set for circular rotation—these are called the galactic constants. Oort maintained a keen interest in the determination of the galactic constants. The values of this set as agreed upon by the International Astronomical Union (IAU) in 1965 were: $A=15\,\mathrm{km\ s^{-1}\ kpc^{-1}}$, $B=-10\,\mathrm{km\ s^{-1}\ kpc^{-1}}$, $R_0=10$ kpc, $\Theta_0=250\,\mathrm{km\ s^{-1}}$. It is extremely important that a standardized set be used by all astronomers since that would allow inter-comparison of data, and kinematical and dynamical results by various workers.

The current estimates of R_0 and Θ_0 give smaller values. This decrease is mainly due to a better measurement of the absolute magnitude of RR Lyrae stars which are now known to be a magnitude (or ~ 2.5 times) fainter than the earlier value. The new set of galactic constants set by the IAU is : $R_0=8.5$ kpc, $\Theta_0=220\,\mathrm{km\ s^{-1}}$ (ref. 10). The generally agreed values for A and B (round to within the error-bars) are $A=14\,\mathrm{km\ s^{-1}\ kpc^{-1}}$, $B=-12\,\mathrm{km\ s^{-1}\ kpc^{-1}}$. These are closer to a flat rotation curve than the earlier values. To within the error bars this new set is also internally consistent. In the next few years high precision astrometry data are expected to become available from the space mission of Hipparchos, and the Hubble Space Telescope. This will then lead to a faster and more accurate determination of the Oort constants A and B.

Observations of galactic rotation

Oort also made a major contribution to the observations of galactic rotation. In fact, Oort was the main driving force in establishing radio astronomy in the Netherlands in the early fifties[11], which led to their detection of 21 cm emission from atomic hydrogen[12] simultaneously with that in the US and in Australia. Oort realized early on that this was an ideal way of obtaining the rotation law at all radii inside of the solar distance ($R \leq R_0$), which then led to the first measurement of the galactic rotation curve in the inner Galaxy[12]. In the analysis of these data, a generalized form of eq. (1), valid for large $d \sim R_0$, was used. It is harder to measure the rotation curve at $R > R_0$ since one needs an independent distance indicator. The rotation curve has now been measured up to about 18 kpc (refs. 13, 14).

Oort also realized early on the importance of studying external galaxies by 21 cm radio emission so as to study their structure and rotation curves, and their gas contents. He was responsible for getting the WSRT (Westerbork Synthesis Radio Telescope) project going[15] and to date some of the best work in this area comes from the WSRT. Consider, for example, the Ph D thesis by Bosma[16] where he mapped a large sample of galaxies in 21 cm to obtain their gas distribution, and the rotation curves and studied these as a function of the morphological type. This work and the contemporary work by Rubin *et al.*[17] showed the existence of extended galactic disks with flat rotation curves with the very important implication of the existence of dark matter in galaxies.

Oort thus brought a cohesive approach to the study of galaxies, using theoretical and/or observational techniques as necessary, so as to obtain a correct, global understanding of galaxies.

The topic of galactic rotation was thus truly established by Oort's work. This remained his cherished area of research and he returned to this and the related topics of galactic structure and dynamics for years later on. The range of topics studied and often initiated by Oort is vast. These include, the Galactic centre, high velocity clouds, radio galaxies, and the other topics covered at this meeting, to give a few examples. Oort probably has had, directly and indirectly through his papers and the people trained by him, the most profound influence on the 20th century astronomy.

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Jan Oort and interstellar clouds

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WHEN Jan Oort embarked on his astronomical career in the nineteen twenties, the existence of interstellar matter was not yet firmly established and the concept of a cloudy interstellar medium was yet to be born. The first important paper[1] of Oort on the Interstellar Medium was concerned with a study of the distribution of interstellar dust in our Galaxy. Some years later Oort wrote another paper[2] with van de Hulst titled 'Gas and smoke in interstellar space' which dealt with the problems of production of gas through volatilization of solid particles by mutual encounters in the interstellar medium. This paper produced the well known Oort–van de Hulst size distribution of interstellar grains.

By the time Oort was invited to deliver the George Darwin lecture[3] to the Royal Astronomical Society (May 10, 1946), enough observational material had accumulated on the nature of distribution of the interstellar material and its kinematics. In the Darwin lecture Oort emphasized on the unevenness of this distribution and used rather liberally the word 'clouds' to describe clumps of interstellar material. Observations by Merrill, Wilson, Adams and coworkers[4–6] had shown that the clouds had considerable random motions ($\geq \pm 15$ km s^{-1}) with respect to the local standard of rest and although Oort's thoughts on the origin of these motions had not yet crystallized, he speculated on the connection between differential galactic rotation and the random motion of the clouds. He also realized that because of the large random motions the clouds might frequently collide and in the event of such a collision, their kinetic energy might be converted to heat and radiation. Hence clouds had to be continually created so that a steady population of them is maintained with the observed large random motions. Quite naturally, Oort was set to think deeply on the coupled problem of origin and acceleration of interstellar clouds and his solution, a few years later, would thus contain answers to both these problems.

Several stimulating developments took place in interstellar matter research soon after the publication of the Darwin lecture which set the stage for Oort's subsequent work on the subject. Adams[7] published the most complete results on velocities of interstellar clouds by analysing high-resolution spectra of Ca II H and K lines in 300 O and B Stars. A detailed analysis of the data by Blaauw[8] led to an exponential distribution of cloud velocities: $P(v)\,dv = \frac{1}{2\eta}\, e^{-|v|/\eta}$, with $\eta = 5$–8 km s^{-1}. It was further noted by Blaauw that some of the components of the interstellar lines had velocities much too great to match even the exponential distribution and that amongst these high velocities negative velocities preponderated. These observations seemed to suggest that the clouds were accelerated in the neighbourhood of the hot stars in whose spectra they were viewed. The other development concerned a study of the thermal properties of the ionized (H II) and neutral (H I) regions. In a paper nearly ten years earlier Strömgren[9] had shown that massive stars born inside an interstellar cloud photoionized the gas in its vicinity and produced an ionized region, whose size depended on the ambient gas density and the luminosity of ionizing photons from the star. The ionized region had rather sharp boundaries and was separated from the outer neutral region by a thin ionization front. Studies by Spitzer[10,11] and coworkers showed that H II regions had considerable thermal energy and pressure (kinetic temperatures $\sim 10^4$ K) while the surrounding neutral portions had much less (kinetic temperatures $\sim 10^2$ K). As a result a pressure gradient of at least two orders of magnitude would act across the ionization front forcing the hot gas to expand. This expansion, in turn, would drive the neutral material outward with velocities similar to the observed cloud velocities in the interstellar medium. Oort was quick to realize the dynamical consequences of expanding H II regions and saw in them the most obvious way of creating and accelerating clouds. While at Princeton University as a Visiting Professor in 1954 he worked out together with Lyman Spitzer the dynamics of the interaction between hot young stars and the interstellar medium. He wrote two papers, the first by himself[12] and the second jointly

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