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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 ~ 10^4 K) while the surrounding neutral portions had much less (kinetic temperatures ~ 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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Based on a talk given at the Neighbourhood Astronomy Meeting held in IIA, 31 March 1993.

with Spitzer[13]. These papers remain todate two of the most important papers on the dynamics of interstellar clouds. In the first paper Oort calculated from a simple momentum conservation argument the acceleration of the neutral shell surrounding an H II region. From his simple calculation he was able to show that the neutral shell may attain final velocities in the range 25–59 km s^{-1} depending on the ratio of the final neutral shell mass to the original mass of the cloud. He then wrote: 'It is clear that while the "radius" of the shell grows it must, by its inherent irregularity as well as by the sweeping up of irregularly distributed interstellar matter, break up into separate parts that will evidently have greatly varying sizes and forms, but will all be very flat. We may identify these fragments with newly formed "ordinary" interstellar clouds.'

In the other paper, Oort and Spitzer worked out the basic rocket mechanism of acceleration of clouds, known since as the Oort–Spitzer mechanism. The authors envisaged the situation as follows:

'Consider what happens to a cloud when it becomes exposed to ultraviolet radiation from an O star. The H atoms near the surface will evidently become ionized. The photoelectrons will escape with several volts of kinetic energy, and the kinetic temperature of the gas will rise, approaching some 10,000° as the ionization approaches completeness. As the surface layer of gas becomes ionized, it will become transparent to ultraviolet radiation, and the region of ionized H will eat its way into the H I cloud. The problem will be simplified by assuming that the density in the region between the O star and the cloud is much lower than that of the cloud, so that the ionized layer can expand more or less freely in the direction toward the O star'.

'The heating of the dense gas in the surface layer of the cloud will produce large dynamical effects. Evidently, an increase of temperature by a factor of 100 will increase the pressure by the same factor, and the gas will tend to expand vigorously. Expansion into the material of the cloud is soon stopped by the large amount of dense material there. In the direction away from the cloud, toward the O star, the heated gas "sees" only a low-density medium and expands in very much the same way as it would into a vacuum. Thus most of the cloud material ionized by the O star will escape from the cloud. This material will be moving preponderantly in the direction of the O star, with a mean velocity relative to the cloud which we shall denote by V. Evidently, the escaping material must have an equal and opposite reaction on the cloud; in other words, it behaves precisely as a jet from a rocket and will accelerate the cloud away from the ionizing star.'

The idealized first case they considered was that of an O star formed at a certain distance from an isolated dense cloud. They also considered a second case—that of a neutral cloud moving into an HII region with a certain velocity and a third case—the birth of O stars within a large, more or less homogeneous mass of interstellar gas.

The authors showed that very high velocities could be attained and that it was possible to explain by such mechanisms the high velocities that are observed in the faint components of interstellar lines.

In the early sixties Oort and his Dutch colleagues[14] were responsible for the discovery of high velocity hydrogen clouds at high galactic latitudes. These were discovered in the 21 cm H I line and with a handful of exceptions they have not been observed so far in any other way. A good part of Oort's scientific efforts in the sixties and subsequent decades was devoted to research on high velocity clouds (HVCs). By definition HVCs are clouds at $|b|>15°$ discovered through their 21 cm emission whose velocities are inconsistent with the standard model of differential galactic rotation of a thin flat disk. Even amongst the HVCs there are subdivisions: the intermediate velocity clouds or IVCs are those with $20\,\mathrm{km\,s^{-1}} \leq |v| < 80\,\mathrm{km\,s^{-1}}$, while those with $80\,\mathrm{km\,s^{-1}} \leq |v| < 200\,\mathrm{km\,s^{-1}}$ are the HVCs; in addition, there are very high velocity clouds or VHVCs which have velocities in excess of $200\,\mathrm{km\,s^{-1}}$. Early observations indicated that all HVCs have negative velocities but in the recent more complete surveys positive components of velocities have been identified. But the VHVCs are almost exclusively seen only at negative velocities and in the Southern Galactic hemisphere.

The preponderance of negative velocities of HVCs led Oort[15] to suggest that these clouds represent primordial intergalactic material falling on to the plane of the Galaxy. He further conjectured that this is how disk galaxies may be forming. In this picture intergalactic gas at velocities of approximately $500\,\mathrm{km\,s^{-1}}$ is assumed to be falling in and getting decelerated in the halo. The gas carries with it primordial angular momentum. Oort inferred an infall rate of $1\,M_{\odot}\,\mathrm{yr}^{-1}$ from the existing observations.

The most notorious problem about HVCs is their unknown distance. Enormous efforts have gone into identifying features which would give clues to their distances but success has been rather rare. The extragalactic origin of these clouds especially the very high velocity ones is by no means ruled out. In one or two cases there is even some observational support. Although Oort's model has been criticised on various grounds and viable alternatives have been proposed, it has shown remarkable resilience and has not been totally disfavoured. The intergalactic gas reservoirs which might give rise to the VHVC's have been looked for but not found so far. More sensitive searches in future may yet discover them and vindicate Oort's hypothesis about the origin of high velocity clouds and formation of galaxies.

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Oort's 1965 review of stellar dynamics

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Original and productive scientists often fight shy of writing review articles. One therefore sees an interesting and different facet of Oort's scientific personality revealed in the review article on stellar dynamics which he contributed to the famous *Stars and Stellar Systems* series initiated by Kuiper and Middlehurst and published by the University of Chicago Press. Volume V of this series was edited by Blaauw and Schmidt and devoted to Galactic structure. Given that the subject of stellar dynamics had already been covered in treatises by the likes of Eddington, Jeans, and Chandrasekhar, it is natural to ask what was Oort's special touch in these fortysix pages (plus an appendix) which have rightly been required reading ever since for entrants to the subject. The first characteristic is that material not directly connected with observations of our Galaxy or their interpretation is uncompromisingly omitted. Equally ruthlessly, all mathematical derivations are left out, giving reference to where they may be found. In lesser hands, this approach would have produced a fragmented and unreadable compendium. It does not, in this article, for two reasons. For one thing, physical principles and interpretation of the equations are given a full and clear discussion. Secondly, the ordering of the material is very logical — random motions, vertical motions, circular motion, small and then large deviations from circular motion. The primary requisites of a review article, readability and comprehensibility, are present in full measure.

Coming to individual sections, the one on motion perpendicular to the galactic plane represents the author's own special interests and contributions. The basic method, due to Oort himself, of determining the mass density from the vertical distribution and velocities of a group of stars (K. giants) is straightforward at least with hindsight. What is special is the insistence on precise numbers and the careful comparison of the dynamical estimate with known forms of matter — stellar and gaseous. Even when direct observations were not available at that time, as in the case of molecular hydrogen, ingenious astrophysical arguments are advanced to constrain the density. The final conclusion, that about half the mass density in the midplane of the Galaxy is in some unknown form, has not really been disproved by later work, and continues to intrigue astronomers even at present when the empirical data and computational power have multiplied manifold. This is one factor of two which is vital to astrophysics! One may remark in passing that in discussing the physical basis of the study of vertical motions, Oort relies more on the properties of individual orbits rather than on constants of motion (i.e., Jeans theorem). This passage has the basic idea of Schwarzschild's computational approach to galaxy dynamics which proved so useful more than a decade later.

The section on small deviations from circular motion is of course based on Oort's early work on galactic differential rotation, a topic covered in more detail in Chanda Jog's article in this issue. Again, Oort's attention goes unerringly to the empirical fact which may be telling us something new — the so-called 'vertex deviation'. The principal axes of the distribution of random velocities deviate from what the simplest model would predict, viz. parallel and perpendicular to the direction of the galactic centre. Non-circular motions due to spiral structure are brought in as a possible cause. Another interesting observed effect which is discussed is 'asymmetric drift'. This asymmetry between the numbers of stars moving faster and slower than the