THE CONTINENTAL CRUST AND ITS MINERAL DEPOSITS

Edited by
D.W. Strangway

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THE CONTINENTAL CRUST AND ITS MINERAL DEPOSITS

The Proceedings of a symposium
held in honour of
J. Tuzo Wilson
held at Toronto, May 1979

Edited by
D.W. Strangway

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D.W. Strangway, J.T. Wilson and Sir Edward Bullard
on the occasion of the Wilson Symposium.

PREFACE

In May of 1979 a group of friends and colleagues gathered to honour J. Tuzo Wilson, a long time member of the faculty at the University of Toronto and now the Director of the Ontario Science Centre. The papers in the symposium on "The Continental Crust and its Mineral Deposits" were presented under the following groupings: i) The Early Earth; ii) Evolution of the Precambrian Crust; iii) Vertical Geometry of the Crust; iv) Crustal Motions; v) The Global View; vi) Ore Deposits. From a study of the Table of Contents, one can see that the conference covered a wide range of topics on the current view of the Earth and its processes ranging from its formation to the movements of fluids leading to the concentration of useful mineral deposits.

It is particularly fitting that this conference should have taken place in Toronto with this broad range of topics, since Tuzo's views of the Earth have had a profound influence on models of terrestrial processes and since there is a great deal of mineral exploration work based in Toronto. Tuzo's early work involved field mapping in the Canadian shield and in Montana. He was instrumental in compiling the first glacial map of Canada and was among the first to recognize how isotopic dating could be used to divide the shield into various age provinces. He used this as the base for his models of stable, fixed continental nucleii. He compiled information on island arcs and championed the contracting Earth theories. This was converted later to support of the expanding Earth hypothesis, but eventually after a thorough synthesis of all known information on ocean islands, he became one of the staunch supporters of the new plate tectonics. He predicted transform faults and championed the concept of hot spots.

There is no doubt that Tuzo's thinking on Earth processes has contributed in a major way to our present models of the Earth. This conference was about this topic and how these models have affected geologic thinking. Each speaker was asked to give his view of current thinking in his sector of the discipline. They were not asked to give a history. In a sense then, the conference was really about the second generation of the plate tectonics revolution. Forty-three papers were presented at the conference with adequate time for discussion. There were no multiple sessions, so that workers from all of the Earth Science disciplines, listened to papers from other disciplines and participated in animated discussion. We have been able to publish in this volume thirty-nine of these papers. This volume represents a snapshot of the 1979 view of the Earth and we hope it will stand as a useful reference work.

Over 300 people attended the conference representing industry, government and university and they came from Canada, the United States, Britain, India, Belgium, Venezuela, Japan and Australia. During the conference, a banquet was held in Tuzo's honour. The featured speaker was Sir Edward Bullard. It was particularly appropriate that Sir Edward was able to come to this conference. Sir Edward had been head of the Physics Department at Toronto when Tuzo was a struggling young professor. He had been at Cambridge when the transform fault theory was generated and sea floor lineations were recognized. Sir Edward himself was a pioneer, who had been responsible for much of the data on which Tuzo's models were built. In fact, one even supposes that Sir Edward may have helped in the conversion of Wilson, when he jumped on the moving continents. Sir Edward passed on the Albatross award to Tuzo at this meeting. His "unusual contribution to oceanography" was "making the faults run backwards". It is therefore with much regret that we record that early in 1980, Sir Edward passed away after a struggle with cancer.

D.W. Strangway
June 1980

Note: Re paper by S.D. Scott on "Geology and Structural Control of Kuroko-type Massive Sulphide Deposits", p. 705-721. Due to a printing error, several pages are out of order. The sequence should be ... 710, 711, 714, 715, 712, 713, 716, 717...

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NUMERICAL CALCULATIONS RELEVANT TO THE ACCUMULATION OF THE TERRESTRIAL PLANETS

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ABSTRACT

A well-defined problem relevant to planetary accumulation is the velocity distribution of a swarm of bodies in heliocentric orbits undergoing mutual collisions and gravitational perturbations. The extent to which the gravitational perturbations counteract the tendency of collisions to circularize the orbits determines whether the swarm will accumulate into four terrestrial planets, or into a larger number of smaller bodies in concentric orbits.

The most extensive treatment of this problem has been given by Safronov. In this analytical theory Keplerian motion is not explicitly introduced, but its effects are calculated by use of an analogy with the dynamics of a rotating fluid. In order to test the validity of this analogy, numerical calculations have been carried out for a problem which can also be treated by Safronov's approach: the evolution of the velocity distribution of a swarm of non-accreting bodies of equal mass. It is found that steady-state relative velocities are achieved which vary with the mass of the bodies in the manner predicted by Safronov, i.e., the mean relative velocity is always comparable to the escape velocity. In addition to the increase in eccentricity and inclination associated with the velocity increase, a radial "diffusion" in semi-major axes accompanies it as well. The velocity distribution is somewhat non-maxwellian.

When accretion is permitted, four or five large planets result, independent of the initial eccentricity. In earlier two-dimensional calculations, Cox found that a small number of large planets were formed only when the initial eccentricity was as high as 0.15. In the present work, Cox's result is reproduced for the two-dimensional case. Thus, although it is possible that the difference between the present and the earlier work arises from the approximations made here, it is more likely that Cox's result is peculiar to the two-dimensional case. Further work is required to learn the conditions under which a more realistic swarm of bodies with varying mass and hence greater collisional damping can evolve into a system resembling that of the present planets.

RÉSUMÉ

La répartition des vitesses d'un ensemble de corps célestes en orbite héliocentrique, subissant des collisions et des perturbations gravitationnelles mutuelles est un problème classique relatif à l'accumulation planétaire. L'accumulation de cet ensemble en quatre planètes terrestres ou en un grand nombre de plus petits corps en orbites concentriques est déterminée par la capacité des perturbations gravitationnelles à contrebalancer la circularisation des orbites sous l'effet des collisions.

Le traitement le plus complet de ce probleme a été donné par Safronov. Dans son analyse théorique le mouvement Keplerien n'est pas introduit explicitement mais ses effets sont calculés par analogie avec la dynamique d'un fluide en rotation. Afin d'évaluer la validité de cette analogie on effectue numériquement la résolution d'un problème qui peut être abordé par la methode de Safronov: évolution de la distribution des vitesses dans un ensemble de corps célestes de même masse ne subissant pas l'accrétion. On trouve que les vitesses relatives, à l'état stationnaire, varient avec la masse des corps selon les prédictions de Safronov, c'est à dire que la vitesse relative moyenne est toujours du même ordre que la vitesse de libération. En plus de l'accroissement de l'excentricité et de l'inclinaison associées à l'augmentation de la vitesse, une "diffusion" radiale des demis grands axes intervient aussi. La distribution des vitesses n'est pas tout à fait maxwellienne.

Lorsqu'on introduit la possibilité d'accrétion, il en résulte quatre on cinq grandes planètes independamment de l'excentricité initiale. Précédemment sur la base de calculs bidimensionnels, Cox a trouvé qu'un petit nombre de planètes se forme seulement si l'excentricité initiale est au moins 0,15. Dans le présent travail nous avons pu reproduire le résultat de Cox pour un modèle bidimensionnel. En conséquence, bien que la divergence entre ces deux travaux puisse provenir des approximations que nous avons faites, il est plus probable que le resultat de Cox reflète une particularité du modèle à deux dimensions. D'autres études sont nécessaires pour savoir dans quelles conditions, le cas plus réaliste d'un groupe de corps de masses variées, ayant donc un amortissement des collisions plus important, peut evoluer en un système ressemblant à celui des planètes actuelles.

INTRODUCTION

In the past several years there has been increasing interest in "comparative planetology" – the relationships between the larger and smaller bodies of the solar system and what they have to teach us about one another. The initial boundary conditions for these bodies, in other words, knowledge of the origin of the solar system, are now coming to occupy a more central place in the thinking of the working scientist. In the past such theories were principally used to satisfy our need for a creation myth and to serve as introductory material for textbooks with no substantial consequences to the further development of the subject. Unfortunately, we are far from an adequate understanding of these initial conditions, and there is much work which must be done if this situation is to improve.

For the most part theories of the origin of the solar system have attempted to describe a single mechanism responsible for the formation of at least the major and terrestrial planets. Once past the initial stages, which are properly part of the problem of star formation, these mechanisms fall into two general categories: 1) those in which massive gravitational instabilities lead to the formation of large gaseous protoplanets (e.g., Kuiper, 1951; McCrea, 1960; Cameron, 1978), and 2) those in which gravitational instability plays only a minor role, if any, and the planets grow by the continuing sweeping up of smaller bodies by larger ones (e.g., Chamberlin, 1904; Safronov, 1969; Weidenschilling, 1974, 1976; Hayashi *et al.*, 1977; Greenberg *et al.*; 1978; Cox, 1978). Qualitative "scenarios" for the formation of all of the planets by one or the other of these mechanisms have been described. The problem with such scenarios is that experience shows that only a small fraction of one's qualitatively appealing ideas survive more detailed quantitative discussion. Progress toward the goal of understanding how the solar system formed will therefore require "rolling up our sleeves" and making detailed quantitative studies of each of the stages of planetary growth described in less quantitative theories. It seems quite possible that this will show that fundamentally different processes were involved in the formation of the major and terrestrial planets.

An insufficient quantity of detailed work of this kind exists at present. The few detailed studies have concentrated on a quantitative treatment of the gravitational accumulation of planets by mutual collisions of planetesimals in the 1 to 1000 km range, principally assuming gas-free accumulation. Gas-free accumulation is not an attractive way for major planets to have formed. However, the volatile-poor composition of the terrestrial planets together with the difficulty of obtaining planet-sized gravitational instabilities at small heliocentric distances have led a number of workers to explore more thoroughly the possibility that at least these planets formed by the "sweeping-up" process under conditions in which gas drag was not important.

Major contributions to the solution of this limited problem have been made by Safronov and his co-workers (Safronov, 1969; Zvyagina *et al.*, 1973; Safronov, 1978). These investigators applied the stellar dynamical techniques of Chandrasekhar (1942) to the problem of the dynamical evolution of a growing swarm of planetesimals: relative velocities increase by mutual gravitational perturbations, and decrease by dissipative collisions and the averaging of velocities accompanying the cohesive collisions responsible for planetary growth. Subject to certain assumptions, these workers calculated that such a swarm can achieve quasi-steady states for both the velocity and the size distribution of the planetesimals.

The result for the velocity distribution is particularly significant. Most other workers have introduced the relative velocity of the planetesimals as a free parameter. If the relative velocity is too high, e.g., several times the gravitational escape velocity of the growing planet, fragmentation rather than accumulation will be dominant, and planets won't grow. On the other hand, if relative velocities are too low, the system of planetesimals will be in nearly circular concentric orbits, and the collisions required for growth will not take place. Building upon the earlier work of Gurevich and Lebedinskii (1950), Safronov (1962) showed that it was not necessary to avoid this problem by the ad hoc introduction of a suitable relative velocity. Rather, he showed that for plausible assumptions regarding dissipation of energy in collisions, and size distribution of the bodies, the mutual gravitational perturbations of the bodies caused their mean relative velocity to be only somewhat less than the escape velocity of the larger bodies. Thus throughout the entire course of planetary growth, from 1-km planetesimals to Earth-sized planets, the system regulated itself in such a way that the larger bodies could always grow, whereas smaller objects would fragment, establishing a spectrum of sizes in the smaller planetesimal mass range.

Despite this success, as well as other important achievements, this theoretical work has its limitations, and even its major conclusions have been questioned (Greenberg *et al.*, 1978; Levin, 1978). One limitation is the difficulty of treating analytically the coupled evolution of the mass and velocity distribution. While the existence of consistent and acceptable approximate steady-state solutions for both of these quantities can be demonstrated, it is difficult to show that the system will actually evolve into these steady-states. For example, Greenberg *et al.* (1978) present numerical simulations of the earliest stages of this growth which suggest that the early formation of a few larger (~1000 km diameter) bodies while most of the mass of the system remains in about 1 km bodies may preclude the development of the higher velocities inferred by Safronov, which may be necessary if planetary growth is to proceed (e.g., discussed in Wetherill, 1978).

Another possible limitation results from the fact that the dynamical theory of Chandrasekhar, upon which Safronov's work is based, does not explicitly consider the planetesimals to be constrained to move in heliocentric Keplerian orbits. Instead, the swarm is treated as analogous to molecules in the kinetic theory of gases. Safronov introduced the effects of Keplerian motion by an ingenious analogy with Prandtl's semi-empirical theory of turbulence in a rotating viscous fluid. In this analogy, the shearing forces resulting from the differential circular velocities of bodies at different heliocentric distances give rise to a partition between turbulent random motion and organized circular motion. More recently Kaula (1980) has used Chandrasekhar's work in a somewhat different way, but still within the "kinetic theory of gases" framework.

In the present work numerical calculations are reported which explicitly involve Keplerian motion. They address two problems relevant to terrestrial planet accumulation:

1) *The orbital evolution in a gas-free medium of a swarm of equal-sized non-accreting bodies that are subject to mutual gravitational perturbations and collisional damping.* This calculation, although far from being a simulation of real terrestrial planet formation, includes the essential physical basis of the Safronov steady-state velocity distribution, and permits a comparison of analytical theory with numerical calculations.

2) *The three-dimensional accumulation of a swarm of large bodies, taking into account mutual gravitational perturbations, collisional damping and cohesion (accretion).* This is a three-dimensional version of a similar problem investigated in two dimensions by Cox (1978). Cox's work, involving more rigorous dynamical procedures than those of the present work, led to the result that unless initial velocities were implausibly large, the swarm would evolve into a system of 8 to 10 small terrestrial planets, rather than into the observed two large bodies and two smaller bodies. In the present work, the two-dimensional results of Cox are reproduced and extended to the three-dimensional case.

STEADY-STATE VELOCITY DISTRIBUTION OF A NON-ACCRETING SWARM

One hundred bodies of equal mass are assumed to have their initial semi-major axes distributed at random over the narrow range 0.96 to 1.04 A.U., with random initial eccentricities less than 0.01 and initial inclinations less than 0.01 radians. Because of