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类地行星及其卫星表面的多环盆地起源模型

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The Origin of Multi-Ring Basins on the Surfaces of Terrestrial Planets and Their Satellites

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摘　要

陨击坑普遍存在于所有的类地行星、月球以及木星与土星的大多数卫星上。对于月球和水星，陨击坑更是其表面主要的地形特征。采样和遥感数据表明陨击成坑对月壳的演化有着深刻和长期的影响。所有陨击坑中最重要的是直径可达 1000 km 的多环盆地，39 亿年前陨星撞击月球表面所携带的质量和能量的主要部分就是以这些盆地的形式展现出来。正确理解多环盆地对于解释月球高地的演化和解释其它行星表面古老的、多坑地区是关键的。但是，大的撞击结构的形成仍是许多成坑问题中尚有争论且知之甚少的问题之一，甚至对于初始弹坑的大小和形状以及环的形成这些根本性问题目前也没有形成一致的看法。

现有的多环盆地环的形成假设分为三组：结构、波形和目标强度。由于环的形成与盆地的挖掘过程有关系，因此这三组假设又可按照盆地挖掘的假设--瞬时弹坑的比例和非比例增长分为两类。可以说没有一个模型获得世人公认，但是多环盆地环间距具有从内向外逐渐增大，且相邻两个环间距满足关系 $2^{0.5}$ D（D 为环间距）的特点被认为是多环盆地起源模型研究中的一个重要方面，任何模型要想很好的解释多环盆地的起源，都必须合理解释环间距的问题。目前，能够较好解释上述间距规律的模型只有海啸模型，其基本思想是：一个盆地大小的撞击事件将会使峰值压力大于岩石破裂压范围内的固体物质发生“液化”，撞击产生的海啸波通过该流体区运动；在这个范围之外的岩石不再以流体形式运动，海啸作用停止和流体呈“冻结”状。

Van Dorn 在尝试用海啸模型解释月球上的多环盆地环间距时，采用的是初始扰动为形变扰动，并假定液化深度为均匀有限深和不考虑粘滞性情况下的浅水波理论，得出的结论是环的形成是重力波在一个叠加于刚性基底上深度为 50 km 的液体层上传播的结果，并认为当时月壳的厚度普遍为 50 km。此后，Yue 等利用初始条件为冲击压时的浅水波理论，通过比较月球上三个不同的多环盆地讨论了多环盆地海啸模型的适用范围，即海啸模型仅适用于主环以内。

本论文就是在前人的研究基础上，针对多环盆地起源的海啸模型进行了深入研究，主要开展了以下两方面的工作：

（1）撞击过程中瞬时弹坑的形成时间估计

采用初始扰动为抛物面形弹坑情况下的浅水波理论，对多环盆地形成的海啸模型进行了讨论，得出了计算环位置的公式。此外，在假定液化深度相同的情况下，与初始扰动为冲击压情况下的浅水波理论得出的环位置公式进行比较，发现利用初始扰动为抛物面形弹坑计算出的盆地内保持液化的时间小，这个时间差可解释为从撞击开始到形成抛物面形瞬时弹坑所需的时间。

（2）多环盆地起源的深水波理论

多环盆地起源的浅水波理论有一明显的缺陷，就是要求在三个不同的类地行星上的每一个盆地撞击点具有相似的壳层结构。基于巨大的高速碰撞将会在被撞星体上形成一个近似半球形的熔化区这一研究结果，我们提出了多环盆地起源的深水波理论，求出了在深水波情况下用于计算环位置的公式。应用到月球、水星、火星上的多环结构时，计算值与观测符合较好，同样可以解释主环以内环间距 $2^{0.5}$ D 的间距规律，且可以避免多环盆地起源的浅水波理论所存在的缺陷。

关键词：类地行星，陨击坑，多环盆地，环间距，起源模型

ABSTRACT

Impact craters occur on all the terrestrial planets and the moon, as well as on most of the larger satellites of Jupiter and Saturn. On less-evolved bodies, such as the moon and Mercury, craters are major landforms. Samples and remote sensing data have highlighted the profound and long-lasting effects of cratering on lunar crustal evolution. The most important craters are the large multi-ring basins with diameter up to 1000 km. The major fraction of the mass and kinetic energy delivered by impacting bodies to the lunar surface before approximately 3.9 b.y. ago is expressed in these basins. An understanding of multi-ring basins is thus critical to the interpretation of evolution of the lunar highlands and of the ancient, cratered terrains of other planets. Unfortunately, the formation of large impact structures is one of the more contentious and poorly understood problems of cratering. There is no apparent consensus on such fundamentals as the size and shape of the original cavity and how it evolves to produce the multi-ring form.

The ring-forming hypotheses of multi-ring basins may be divided into three groups: structural, wave form and target strength. Because the ring problem has been linked to that of basin excavation, these three group hypotheses, in turn, are related to two classes of hypotheses for basin excavation: proportional and non-proportional growth of the transient cavity. There is no any of these models be accepted widely, but the average $2^{0.5}$ D spacing of basin rings may provide certain constrains on the formation model of impact basins on the planets and satellites. At present, the only model has been proposed to account for the spacing of basin rings is tsunami model. The basic idea of this model is that a basin-size impact would release the energies and “fluidize” the lunar rocks in some fashions, so that tsunami-like waves could radiate from the impact point, after the peak shock pressure had reduced to the rock-failure pressure, the wave froze into position as a ripple in the Moon’s crust.

To reconcile the tsunami model with the observed spacing of Mare Orientale, Van Dorn adopted the theory of shallow water waves generated by an initial deformation. His solutions show that gravity wave disturbances on a 50 km “liquid” layer above a rigid basement can fit the ring spacing. One year later, he drew the conclusion that the 50 km layer was a general feature of the lunar crust during mare formation. Yue et.al. rediscussed the tsunami model using theory of shallow water waves generated by an impulsive pressure, from their computational results, they thought the tsunami model can only be applied to the area within the IV ring, and this ring marks not only the crater rim of the excavated basin but also the end of the fluidized region.

This dissertation is based on the work of former researchers, and carries out further research to the tsunami model. More details of our study are offered as follows.

(1) The formation time of transient crater

The tsunami model of the origin of multi-ring basins has been analysed with the theory of shallow water waves generated by an initial surface deformation, which is

set as a parabolic crater. An approximate formula for calculating the ring radius has been derived. Besides this, by comparing the result of initial impulsive pressure disturbance with initial deformation disturbance under the condition of same fluidized depth, it seems that the time of the interior of crater appears to behave in a fluid-like manner in the case of initial deformation disturbance is shorter than the case of initial impulsive pressure disturbance, this time difference can be explained as the time required from the start of impact to the formation of a parabolic crater.

(2) The deep water waves theory of the origin of multi-ring basins

As there is an obvious drawback that it requires a similar crustal structure at each basin-impact site on all three planets by use of the theory of shallow water waves to discuss the tsunami model. We rediscuss the tsunami model by use of the theory of deep water waves based on the work that a large, high speed impact will creates an approximately hemispherical melt region during late stage accretion, and derive an approximate formula for calculating the ring radius. The formula applied to some multi-ring basins on the Moon, Mercury and Mars, gives almost equidistant spacing ($2^{0.5}$ D) of the rings within the main ring. Besides this, the theory of deep water waves can avoid the drawback of the theory of shallow water waves.

Keyword: terrestrial planets, craters, multi-ring basins, ring spacing, origin model

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