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博士学位论文

接触双小行星(4179) Toutatis的形成机制研究

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摘 要

接触双小行星是一类由明显的两部分结构相接而构成的单小行星，地面雷达观测结果表明直径大于200米的近地小行星中大约14%为接触双小行星，而且目前三个小天体探测任务（隼鸟号、嫦娥二号和罗塞塔号）的探测目标也都具有接触双星结构，可见接触双小行星是一类重要的小行星类型，对其形成机制开展研究能够为深入理解小行星的形成演化提供重要线索。

(4179) Toutatis是一颗受关注较多的S型近地小行星，自从其1989年被发现以来地面雷达和光学望远镜就对该小行星做了大量观测，发现了其缓慢的非主轴自转特性，并且从反演的雷达形状模型来看是一颗接触双小行星。嫦娥二号于2012年12月13日以离表面770米的距离飞越了该小行星，获得了大量高精度光学图像数据，结果证实Toutatis确实是一颗由明显的两部分结构相接组成的接触双小行星，并且在接触位置有一个边缘清晰的直角结构，其体积较大的部分（主瓣）有明显的延长型形状且两部分的连接点位于主瓣的长轴上，从动力学角度来看Toutatis的形状结构处于一个较不稳定的状态。多数学者猜测Toutatis的形状是由其两个组成部分在低速碰撞下形成，但具体的形成过程，包括如何产生这种不稳定的结构仍不清楚。利用Toutatis的雷达形状模型以及嫦娥二号获得的光学探测数据，本文的研究工作主要分为三部分：

首先，利用嫦娥二号探测数据并结合已有的雷达形状模型，通过轮廓匹配方法获得了Toutatis新的三维形状模型。在此基础上，基于Toutatis的形状参数，假设其母体是一颗主星和卫星均为球体的双轨旋同步双小行星，我们通过采用散体动力学数值模拟方法研究了在变化的参数空间下该双小行星“母体”近距离飞越地球的动力学过程。结果表明地球的引力摄动可能导致卫星与主星发生m/s量级的低速相撞，但撞击本身不会对主星的形状产生显著影响，而在选定合适的飞越距离后（大约1.4~1.5倍地球半径），地球潮汐效应在主星和卫星相撞之前会明显改变卫星和主星的形状与自转，并且卫星和主星相撞并合后可以形成类似Toutatis形状的延长型接触双小行星，因此该机制为延长型接触双小行星的形成提供了一种合理的解释。

其次，从嫦娥二号获得的Toutatis光学图像上可以发现其表面分布有222颗直径在10米到61米之间的碎石以及70多个撞击坑，特别是在主瓣端部有一个直径约800米的撞击坑。在强度域假设下，我们基于描述高速撞击溅射物参数分布的

标度律方法获得了从800米撞击坑内抛射出来的溅射物粒子的大小、抛射位置和抛射速度分布，并通过数值模拟研究了这些抛射出来的粒子回落到Toutatis小行星上的比例和位置，结果表明回落粒子的总数目和总体积均明显低于嫦娥二号给出的观测结果，这说明Toutatis表面分布的碎石大部分都不来自于撞击坑，而有可能来源于其形成时候的“母体”。

最后，小行星附近的引力场环境可能对小行星的形成演化机制提供重要约束，同时在我们的工作中为了研究从800米撞击坑内抛射出的溅射物粒子回落到Toutatis表面的位置分布情况，需要对溅射物粒子在小行星引力场影响下的轨道进行外推计算，此时若采用多面体法计算引力场会显著增加计算成本。为了克服这一问题，我们提出应用三维空间中的Chebyshev多项式拟合方法来计算不规则形状小行星附近的引力场。该工作比较了四种引力加速度拟合方式，在充分运用小行星附近引力场变化规律的基础上提出了一种先沿着地平坐标系方向分解再拟合的处理方式，并且提出采用自适应八叉树算法来减小小行星表面附近的引力场拟合误差。以Toutatis为例的数值算例表明该方法能显著提高引力场计算效率，在精度要求不是特别苛刻的情况下可用该方法做轨道积分。

综上所述，本文利用嫦娥二号获得的Toutatis小行星探测数据，通过对双小行星飞越地球过程的数值模拟研究提出了类似Toutatis 延长型接触双小行星的一种形成机制，通过对由标度律方法获得的溅射物粒子的轨道进行数值模拟证明了Toutatis表面的碎石大部分不来自于撞击坑，并针对一般的不规则形状小行星提出了一种基于Chebyshev多项式拟合的引力场快速计算方法。

关键词： Toutatis，接触双小行星，形成演化，高速碰撞，引力场

Abstract

Contact binary asteroids are a kind of single asteroids characterized by their bifurcated configurations (or bi-lobed structure). Ground-based radar observations have shown that contact binaries occupy approximately 14% in the population of near-Earth asteroids with diameter larger than 200 meters, and the targets of three minor planet missions, Hayabusa, Chang'e-2 and Rosetta, are contact binaries. It definitely reveals that contact binary asteroids are important objects for study. The research of formation mechanism of these asteroids may provide keys clues to deep understanding of formation and evolution of the asteroids.

(4179) Toutatis is a prominent S-type near-Earth asteroid. Ground-based radar and optical observation campaigns were performed since its discovery in 1989. The surprising slow non-principal-axis rotation of Toutatis was discovered and the 3D shape constructed with radar data shows this asteroid is a contact binary. Chang'e-2 flew by this asteroid on 13 December, 2012, with the nearest distance away from its surface of approxiamtely 770 m. A series of high-resolution optical images were achieved during the flyby. The true images confirm that Toutatis is a distinct contact binary asteroid composed of two different components. A sharply perpendicular silhouette is observed near the connection area between the components and the big lobe has an obvious elongated shape, with the connection located at the long axis of the big lobe. From a dynamical point of view, the configuration of Toutatis is in an unstable state. The researchers suggest that Toutatis' configuration may come from a low-speed impact between two components, but the detailed formation process, including how to generate such an unstable state, is still not well understood. Based on the radar-derived shape model and the imaged data obtained by Chang'e-2 , our work presented in this dissertation mainly includes the following three parts:

(1) A new 3D shape model of Toutatis is derived by matching the silhouette between the optical images from Chang'e-2 and the existing radar model. Then, based on the derived physical parameters of Toutatis, we assume that the precursor of Toutatis is a doubly synchronous binary asteroid composed of two spherical bodies. The dynamical scenario of the binary precursor flying by the Earth in a close distance is investigated by

adopting the granular dynamical simulations in a varied parameter space. The outcome shows that the gravitational perturbation of Earth may lead to a magnitude of m/s low-speed impact between the primary and secondary while the impact itself has negligible influence on the shape of the primary. But if we choose an appropriate flyby distance (about 1.4~1.5 Earth radius), the tidal effect of Earth may significantly alter the shape and spin of the components prior to their mutual impact, and a newly generated Toutatis-like contact binary asteroid may be reconstructed after the impact accretion. This work gives a new reasonable interpretation for the formation of Toutatis-like elongated contact binary asteroids.

(2) The optical images obtained by Chang'e-2 show that 222 boulders ranging from 10 m to 61 m, as well as over 70 craters, are identified on the surface of Toutatis, especially an 800 m depression in the endpoint of the big lobe. We use the scaling law to obtain the size, position, and velocity distribution of ejecta particles from the 800 m depression under strength regime. Numerical simulations of the particles' orbits are conducted and the reimpacting portions and position distributions are obtained. The results show that the entire number and the volume of reimpacting ejecta particles are obviously lower than the results identified by the observations of Chang'e-2 , which means most of the boulders on the surface of Toutatis had not come from the crater, but may originate from the parent body.

(3) The gravitational environment near an asteroid is a strong constraint on its formation and evolution, and when we study the distribution of reimpacting ejecta coming from the 800 m depression on Toutatis, the particles' orbits are predicted under the gravitational acceleration. The computation cost will be high if we use the polyhedral method to calculate the gravity. To relieve this problem, we present a computation method of gravity near an irregularly-shaped asteroid by adopting 3D Chebyshev polynomials interpolation. We compare four gravity interpolation ways and in consideration of the variation of gravity we propose to adopt a way that the gravitational acceleration is firstly decomposed along the local horizontal coordinate system and then interpolated separately. An error-adaptive octree division scheme is also introduced to reduce the interpolation error near the surface of asteroid. The numerical simulations taking Toutatis as an example show that our method may greatly improve the computation efficiency of gravitational acceleration, and it may well be