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接触双小行星(4179) Toutatis的形成机制研究

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接触双小行星是一类明显由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 m的近地小行星中大约14%为接触双小行星, 而且目前3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. 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1989年发现以来地面雷达和光学望远镜就对该小行星进行了大量观测, 发现其具有缓慢的非主轴自转特性, 并且从反演的雷达形状模型判断其是一颗接触双小行星. 嫦娥二号于2012年12月13日从距离其表面770 m处飞越了该小行星, 获得了大量高精度光学图像数据, 结果证实Toutatis确实是一颗明显由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, 本文主要开展了以下3个部分的研究工作.

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3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(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 m到61 m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 m的撞击坑. 在强度域假设下, 基于描述高速撞击溅射物参数分布的标度律方法, 我们获得了从800 m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值, 这说明Toutatis表面分布的碎石大部分都不来自于撞击, 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. 为了研究从800 m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

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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3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4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高的情况下可用该方法做轨道积分.

Formation Mechanism of Contact Binary Asteroid (4179) Toutatis

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Contact binary asteroids are a kind of single asteroids with bifurcated (or bi-lobed) configurations. Ground-based radar observations have shown that about 14% of near-Earth asteroids larger than 200 meters in diameter may be contact binaries. Specially, the targets of the three minor planet missions, Hayabusa, Chang'e-2, and Rosetta, have contact binary configurations. Contact binaries are an important type of asteroids for completely understanding the formation and evolution of asteroids in the solar system.

(4179) Toutatis is a prominent S-type near-Earth asteroid, and has been observed by many ground-based radar and optical campaigns since it was discovered in 1989. These observations reveal that the asteroid is rotating very slowly around a non-principal axis, and its 3D shape model constructed by radar data indicates that it is a contact binary. Chang'e-2 spacecraft flew by Toutatis on 13 December 2012, with a nearest distance of approximately 770 meters away from its surface. A series of high-resolution optical images taken during the flyby confirm that Toutatis is a distinct contact binary composed of two components. A sharply perpendicular silhouette is observed near the connection area, the big lobe has an obviously elongated shape, and the connection locates at the long axis of the big lobe. From a dynamical point of view, the configuration of Toutatis is in an unstable state. Many researchers suggest that the Toutatis' configuration may come from a low-speed impact between two components, but the detailed formation process that how such an unstable state become realistic is still not well understood. By employing the radar-derived shape model and the optical images obtained by Chang'e-2, the research presented in this dissertation mainly includes the following three parts.

First, a new 3D shape model of Toutatis is derived by matching the silhouette between the Chang'e-2's optical images and the existing radar model. With that, we assume the precursor of Toutatis is a doubly synchronous binary asteroid composed of two spherical bodies. The dynamical scenario that the binary precursor closely encounters the Earth is investigated by applying the granular dynamical simulations in a wide parameter space. The results show that the gravitational perturbation of Earth may lead to a m/s-level low-speed impact between the primary and secondary, while the impact has a negligible influence on the shape of the primary. But if we choose an appropriate flyby distance (about 1.4–1.5 Earth

radii), the Earth's tide may significantly alter the shape and spin of the components prior to their mutual impact, and a Toutatis-like contact binary asteroid may be reconstructed after the impact coalescence. This mechanism gives a new reasonable interpretation for the formation of Toutatis-like elongated contact binary asteroids.

Second, the optical images obtained by Chang'e-2 show that 222 boulders from 10 m to 61 m across, and as well as over 70 craters, are identified from the optical images obtained by Chang'e-2, especially a depression with a diameter of 800 meters locates in the endpoint of the big lobe. We use a scaling-law method to obtain the size, position, and velocity distribution of ejecta particles from the depression under strength regime. Numerical simulations of the particles' orbits are conducted, and the re-impact portions and their position distributions are obtained. The results show that the total number and the volume of re-impact ejecta particles are obviously lower than the results identified by the observations of Chang'e-2, which means that most of the boulders on the surface of Toutatis did not come from the crater, but may originate during formation process of the parent body.

Finally, we discuss the constraint of the gravitational field nearby an asteroid on its formation and evolution. In order to study the distribution of re-impact ejecta coming from the depression on Toutatis, we need to compute the orbits of these ejecta under the gravitational acceleration of Toutatis. However, the computation cost will be high if we use the polyhedral method to calculate the gravity. To eliminate this problem, we present a new method to calculate the gravity near an irregularly-shaped asteroid by adopting the 3D Chebyshev polynomial interpolation. We have compared four different gravity interpolation methods, and the best one is recommended for the efficiency, in which the gravitational acceleration will be 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. We take Toutatis as an example to show that the new method may greatly improve the computation efficiency of near-surface gravitational acceleration, and it may be well used to perform the orbit propagation in case that the precision is not rigorous.