lems with its ephemeris need to be solved if we ever hope to detect the long-term evolution of ring and satellite systems.

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Trapped Coronal Magnetogravity Modes

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Theoretical analyses suggest a physical scenario for the trapping of coronal magnetogravity wave modes above the solar transition region. The shortest oscillation period of coronal magnetogravity modes should be longer than about 1.5 hours. These long-period modes may be responsible for the unexpected low-frequency (1 to 140 microhertz) discrete modes recently discovered in interplanetary charged particle fluxes and magnetic field fluctuations. If the detected modes are caused by these magnetogravity modes rather than by gravity-mode oscillations in the solar interior, then the solar corona and the transition region may be probed from an entirely new perspective by helioseismological techniques. These coronal magnetogravity modes could reveal clues to the heating and dynamics of the solar corona.

Recently, Thomson *et al.* (*1*) reported that discrete low-frequency ($\sim$1 to 140 μHz) modes were detected in low-energy charged particle fluxes measured by Ulysses and Voyager II spacecraft by extensive time-series analysis; they also found similar modes by analyzing earlier magnetic field data from Interplanetary Monitoring Platform 8 and International Sun-Earth Explorer 3 spacecraft. Thomson *et al.* (*1*) tentatively suggested that solar interior gravity modes (*g*-modes) were propagated into the remote solar wind as fluctuations in the interplanetary magnetic field, probably as large-scale Alfvén waves (*2*), although evidence for the necessary physical linkage is apparently lacking at present. It is important to properly identify the physical and dynamic processes that lead to the appearance of these discrete low-frequency modes in order to extract useful information about the sun, its atmosphere, magnetic fields, and wind.

Theoretical models have shown that incompressible Alfvén waves decouple from compressible magnetohydrodynamic (MHD) waves in spherical geometry with a radial magnetic field (*3–6*). Gravity wave motions necessarily involve compressive effects, so it is unclear how *g*-modes trapped deep in the solar interior can be transformed into Alfvén modes propagating in the remote solar wind. Furthermore, if interior *g*-modes were transmitted into interplanetary space, their persistent passage through the photosphere should leave indelible signatures. But no evidence has been firmly established for photospheric manifestations of these interior *g*-modes (*7*). Here I offer an alternative interpretation based on a simple static atmosphere model with the appropriate wave properties to show that discrete magnetogravity modes can be trapped in the lower solar corona above the transition region and that these modes may account for the low-frequency modes detected (*1*).

The continuous expansion of the million-degree magnetized solar corona gives rise to the solar wind in interplanetary space. Close to the sun, the solar wind is sufficiently subsonic that a large coronal hole region within several solar radii can be treated as isothermal and static with a radially open magnetic field. In order to clearly explain MHD wave properties in a magnetized atmosphere and for pedagogical reasons, it would be beneficial to first consider the case without a magnetic field. An unmagnetized atmosphere can support acoustic waves when the angular perturbation frequency ω is higher than the local acoustic cutoff frequency, $\omega_c \equiv \gamma GM_\odot/(2C_s r^2)$ and gravity waves when ω is lower than the local Brunt-Väisälä buoyancy frequency, $N_{BV} \equiv (\gamma -$

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$1)^{1/2}GM_\odot/(C_s r^2)$, where γ is the adiabatic index, G is the gravitational constant, $M_\odot$ is the solar mass, C_s is the isothermal coronal sound speed, and r is the radial distance from the sun's center (8). For typical values of γ (for example, $\gamma = 5/3$), $\omega_c > N_{BV}$ at any given r throughout the corona, and wave perturbations become locally evanescent when $N_{BV} \lesssim \omega \lesssim \omega_c$. Apparently, ω_c and N_{BV} decrease with increasing r, and this fact leads to cavity formation for gravity waves. A low-frequency gravity wave launched above the solar transition region [STR (9)] will propagate into the overlying corona up to a certain radial distance R_G in the midcorona where ω and the local N_{BV} become equal. This gravity wave experiences a strong reflection at R_G due to the presence of an effective propagation barrier (10), and the subsequently induced perturbation beyond R_G becomes evanescent with $N_{BV} \lesssim \omega \lesssim \omega_c$ until another radial distance R_A ($> R_G$) where ω and the local ω_c become equal. Beyond R_A, ω_c falls below ω and the perturbation leaks radially outward in the form of an acoustic wave. An effective propagation barrier is located within the radial range $R_G \lesssim r \lesssim R_A$ with the barrier height and width dependent on spherical harmonic degree ℓ and ω. Typically, the larger the ℓ and the lower the ω, the higher and wider the barrier and thus the more efficiently gravity waves are trapped in $r \lesssim R_G$ (10). This is the basic mechanism for trapping gravity waves in the midcorona, and the dynamic sequence described above has been termed "gravitoacoustic wave transformation" (10, 11). The radial extent R_G of the coronal cavity for trapping gravity waves is frequency-dependent, namely, the lower the ω, the larger the turning point R_G for reflecting gravity waves.

In the absence of a lower reflecting boundary, gravity waves blocked from above would form a continuum in the frequency domain. In order to form discrete gravity wave modes, a cavity must also contain a lower reflecting boundary that is identified with the STR (12) in the present scenario. The transition from the solar chromosphere to the corona is extremely rapid. Over a radial distance of several hundred kilometers across this STR, the mean temperature rises sharply from $\sim 10^4$ K to $\gtrsim 10^6$ K. Because the thermal gas pressure remains nearly constant across the STR, the plasma density drops by a factor of ~ 100, according to the ideal gas law. For waves with large radial scales, the STR can be effectively treated as a spatial discontinuity (13) of temperature and density. In general, the larger the wave speed difference across a discontinuity, the stronger the reflection effect. Specifically, one can show (10) that the reflection coefficient $\mathfrak{R}$ of gravity waves across the STR ranges from ~ 0.67 to 1.0. With such a strong reflection from below by the STR, discrete gravity modes can thus appear in the lower solar corona.

In the presence of a radial magnetic field that scales as r^{-2} in spherical geometry (14), the magnetized corona can support a variety of MHD waves, including modified acoustic-gravity waves. In the linear regime, incompressible transverse Alfvén waves (4, 15) decouple from compressible MHD waves (3, 6). After Fourier transformation in time and angular spherical harmonic decomposition, the equations for three-dimensional compressible MHD perturbations are fourth order and contain information for magnetic waves and magnetoacoustic gravity waves (3, 16). In such a magnetized atmosphere, magnetic waves behave very much like Alfvén waves (4) in terms of the radial scalings of transverse magnetic field and velocity perturbations, except that compressions and thermodynamic variations are involved and angular variations are distinctly different (5). Magnetoacoustic gravity waves (3) are essentially acoustic gravity waves (as explained earlier) associated with magnetic field fluctuations due to the background radial magnetic field. On the basis of a MHD perturbation analysis (16), one can show that magnetoacoustic waves appear for sufficiently high frequencies with $\omega \gtrsim \omega_c$, whereas magnetogravity waves appear in a certain finite low-frequency range $[\ell(\ell + 1)]^{1/2}C_A/r \lesssim \omega \lesssim N_{BV}$, where C_A is the Alfvén wave speed. This low-frequency cutoff of magnetogravity waves is caused primarily by the tendency of the background radial magnetic field to restrict transverse variations in compressible perturbations as a result of magnetic induction; and gravity wave oscillations necessarily involve transverse variations. Therefore, magnetogravity waves with small transverse spatial scales cannot propagate into a region of very high C_A where incurred MHD perturbations will become attenuated. It follows that magnetogravity waves will be reflected in a strongly magnetized and rarefied atmosphere.

The solar coronal heating and the presence of STR are intimately related to the overall structure of magnetic fields pervading the photosphere and chromosphere. The fairly coherent structure of supergranules with typical transverse spatial scales of $\sim 3 \times 10^9$ cm covers the solar photosphere globally (17). Intense magnetic fields ($\sim 10^3$ G) in the fibril state concentrate along boundaries of supergranules. Across the chromosphere, the STR, and into the lower corona, these fibril magnetic fields diverge to compete for available space with increasing height, and thus a bright chromospheric magnetic network appears in ultraviolet emissions (for example, in the C IV line). Above each individual supergranule, there exists a weak-field spatial region whose cross section shrinks with increasing height into the lower corona. Because an individual supergranule is not likely to be completely isolated by surrounding magnetic fibrils, weak-field regions above neighboring supergranules are expected to be topologically connected. Many such weak-field spatial regions can therefore form an overall coherent structure globally over the solar surface or within the base of large coronal holes. Because MHD wave-speed difference is large across the narrow STR as a result of drastic density drop, the STR serves as an effective reflecting boundary for magnetogravity waves. In this scenario, discrete gravity wave modes, affected by magnetic fields, can appear in the coherent structure of weak-field spatial regions above the STR. The most likely sources of persistent excitation for magnetogravity waves are protruding spicules (18) randomly agitating along supergranule boundaries and slow structural variations of supergranules over much longer time scales of a few days.

The discrete low-frequency modes detected in the solar wind (1), if confirmed by further data analyses, provide evidence for the existence of coronal magnetogravity modes trapped in the weak-field spatial regions topologically connected over the global sun. In this scenario, the shortest oscillation period of these magnetogravity modes corresponds to an N_{BV} at the coronal base of about 1.5 hours. Consistent with this observation, the frequency of 185 μHz corresponding to this estimated time scale is higher than the Nyquist frequency of 139 μHz for the hourly averaged data (1). The mean strength of open magnetic fields (~ 1 to 10 G) in the lower corona is sufficiently strong and the plasma number density ($\sim 10^8$ to 10^{10} cm^{-3}) is sufficiently low that C_A ranges from $\sim 10^7$ to 10^8 cm s^{-1}. Therefore, upward-propagating magnetogravity waves, especially those with very low frequencies, will be gradually blocked by coronal magnetic fields.

Meanwhile, coronal magnetic fields are perturbed by impinging gravity wave motions from below; after penetration upward into a radially evanescent region, the remnant compressible MHD perturbation eventually emerges at large radii in the form of magnetoacoustic waves (3, 6) in the solar wind. This dynamic sequence is referred to as "magnetoacoustic gravity wave transformation." I emphasize that, because of the presence of coronal magnetic fields, hydrodynamic cavity sizes (that is, those due solely to the radial falloff of N_{BV}) for low-frequency gravity modes are generally cut short in the radial extent. In my scenario, the information of discrete coronal magnetogravity modes can be naturally transmitted or leaked out by magnetic field fluctuations, and variations of charged particle fluxes are associated with squeezing effects of magnetoacoustic gravity waves in general.

The most stringent test of my proposal (11) is whether similar discrete low-frequency modes can be directly detected in intensity variations and Doppler shifts of appropriate spectral lines (formed in the STR and the lower corona) in ultraviolet, extreme ultraviolet, and x-ray bands during the Solar and Heliospheric Observatory mission successfully launched in December 1995. A thorough understanding of these modes may offer valuable clues for the solution of longstanding problems concerning the heating and dynamics of the solar corona.

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Probing Electrical Transport in Nanomaterials: Conductivity of Individual Carbon Nanotubes

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A general approach has been developed to determine the conductivity of individual nanostructures while simultaneously recording their structure. Conventional lithography has been used to contact electrically single ends of nanomaterials, and a force microscope equipped with a conducting probe tip has been used to map simultaneously the structure and resistance of the portion of the material protruding from the macroscopic contact. Studies of individual carbon nanotubes demonstrate that the structurally most perfect nanotubes have resistivities an order of magnitude lower than those found previously and that defects in the nanotube structure cause substantial increases in the resistivity.

Nanometer-scale structures and molecular materials are of great interest as potential building blocks for future generation electronic devices of greatly reduced size (*1–3*). Rational design of any device will require a fundamental understanding of the properties of these materials and how they depend on, for example, dimensionality and size. For instance, the electrical and mechanical properties of carbon nanotubes have generated considerable interest and speculation (*3–6*), although direct measurements of the intrinsic resistivity and mechanical strength of individual nanotubes has been difficult. Likewise, the term molecular wire has been widely applied to anisotropic molecular materials (*1, 2, 7*), but the meaning of this term relative to an absolute conductivity remains unclear.

The difficulty is in connecting measuring devices from the macroworld to nanometer-scale materials, for which two or more connections are needed. We report a general approach for electrical measurements of nanomaterials and have used this approach to determine the resistivity of individual carbon nanotubes. Our method combines conventional lithography, to electrically contact single ends of nanotubes, and a force microscope equipped with a conducting probe tip, to map simultaneously the structure and resistance of the portions of nanotube that protrude from the macroscopic contact. Defects in the nanotube structure cause substantial increases in the resistivity, and the structurally most perfect nanotubes have resistivities an order of magnitude lower than those found previously (*8–10*).

To measure the electrical properties of individual carbon nanotubes (Fig. 1), we deposited a drop of a nanotube suspension on a flat insulating surface and covered it with a uniform layer of Au. A pattern of open slots was produced in the Au layer by conventional lithography procedures to expose the nanotubes for measurement. Force microscopy studies showed that after this procedure, many of the single nanotubes have one end covered by the Au pattern and the other end extending into an open slot. With a conducting cantilever-tip assembly in the force microscope, it is possible to contact electrically and measure the axial conduction through a single nanotube to the Au contact while simultaneously recording the nanotube structure. Conducting tips were made by depositing NbN onto commercial Si_3N_4 cantilevers. This coating was chosen because it exhibits a combination of good conductivity and hardness. Soft conducting coatings like Au were insufficiently stable to provide reproducible measurements, and heavily doped Si tips, although robust, had excessively large contact resistances to the nanotube samples.

Our approach has some similarities to previous studies of carbon nanotubes (*9, 10*). Langer *et al.* (*9*) used a scanning tunneling microscope to identify nanotube bundles and then expose a resist so that fixed Au contacts could be made to the two ends of a bundle. Studies of nanotube bundles are limited, however, because the sizes and structures of the individual nanotubes in the ensemble are unknown. Measurement of the resistance of a single nanotube has also been reported for the chance occurrence of one nanotube spanning two lithographically patterned macroscopic electrodes (*10*). Both of these reports are two-probe experiments that can be influenced adversely by contact resistance and, in one case (*9*), the uncertainty in the structures of the nanotubes that compose the sample measured. In our studies, we can rapidly identify and focus on individual carbon nanotubes by exploiting the high-resolution imaging capabilities of the force microscope; furthermore, because we determine the resis-

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