ATMOSPHERIC INTERNAL GRAVITY WAVES AS A SOURCE OF QUASIPERIODIC VARIATIONS OF THE COSMIC RAY SECONDARY COMPONENT AND THEIR LIKELY SOLAR ORIGIN*

(Invited Review)

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Abstract. Hard gamma-radiation fluctuations with the periods from 4 to 60 min were investigated in the course of balloon flights at altitudes of 30–40 km. Quasiperiodic intensity variations (QPV) were observed with periods of 5 min, 12–15 min, and 23–26 min, those of 5 min predominating. QPV last no longer than several hours, their associated amplitudes ranging from 5 to 20%. QPV were observed both in mid-latitudes and in the tropics, their detection probability for 3^h exposure being 0.3. In the total charged component QPV with comparable amplitudes were not registered. Synchronous atmospheric pressure variations were recorded practically with an amplitude 20 times less than that of gamma-radiation. This suggest short internal gravity waves (IGW) in the stratosphere in the range from 10 to 100 km as the most likable source of QPV. Since the temperature profile of the Earth atmosphere provides conditions for superdistant waveguiding propagation of short IGW with a period of ~ 5 min at altitudes of 110 and 30 km, the source of waves can be well away from the point of their registration. The IGW generation in the stratosphere can be attributed to the resonance caused by global solar oscillations with low l modes. The resonance probability is likely to be due to the hard solar radiation variations which are absorbed in the ozone layer. The coincidence of the frequency oscillation range in the chromosphere and that of IGW in the stratosphere suggests an IGW resonant excitation mechanism in the Sun–Earth system.

The observations at 46° N geomagnetic latitude (cutoff rigidity $R = 3.5$ GV) and 8° N geomagnetic latitude ($R = 16.9$ GV) by high altitude balloons in 1972–79 recorded quasiperiodic gamma-ray intensity variations (QPV) with an energy of more than 40 MeV (Galper *et al.*) Measurements made with a spark chamber telescope, with a geometrical factor of 115 cm^2 ster and an effective aperture of 40° (Galper *et al.*, 1974) were carried out at altitudes from 4 to 10 g cm^{-2} of the residual atmosphere, the measuring time lasting from 5 to 10 hr.

Simultaneously, the intensity of charged particles was recorded by means of a single counter (the threshold energy of ~ 1 MeV) and a directed counter telescope detecting electrons with energies of more than 60 MeV and protons with energies of more than 300 MeV. The atmospheric pressure was also recorded, a sensor with a precision of 10^{-2} mbar being used in one of the balloon flights.

Time-variation analysis made in the frequency range from 3×10^{-4} to 4×10^{-3} Hz (the associated periods from 4 to 60 min) revealed the following regularities of QPV that might suggest their origin:

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(1) QPV with the periods of 5 min, 12–15 min, and 23–26 min are observed, those of 5 min predominating;

(2) QPV last no longer than several hours, their associated amplitudes ranging from 5 to 20%;

(3) the QPV detection probability for 3 hr exposure is about 0.3;

(4) there are no variations in the charged component, at least with the amplitudes more than 5%;

(5) atmospheric pressure variations were recorded which are prectically synchronous with QPV of gamma-radiation, but with amplitudes smaller by a factor of 20.

It is possible to explain the observed QPV data. Hard gamma-radiation in the stratosphere is likely to be due to the interaction of primary cosmic rays with the matter of the atmosphere. Gamma-ray intensity can be expressed as: $I_\gamma = AI_{CR}(>R)t$, where $I_{CR}(>R)$ is the primary cosmic ray intensity with an energy higher than the local cutoff rigidity R, $t = \int_{z_0}^{\infty} \rho(z)\,dz$ is the thickness of the residual atmosphere, $\rho(z)$ is air density, and z_0 is the balloon altitude. Since the air density changes exponentionally as $\rho(z) \sim e^{-z/H}$, only the thickness of the atmosphere comparable to the standard height $H = 7$ km is essential. The interpretation of QPV in terms of I_{CR} or R variations seems unlikely since no marked variations in the charged component are recorded. In view of modern ideas of internal gravity waves (IGW) it is, however, possible to interpret the obtained data in terms of thickness t variations.

IGW are exhibited in periodic variations of atmospheric parameters, air density in particular (Gossard and Hook, 1978; Hines, 1960). These variations would, in fact, amount to t variations. The representation of an isothermal atmosphere where IGW behave as flat waves will hold as the first approximation. Short IGW with wavelengths of about 100 km are essentially transversal (Golitzin, 1965) and their relative pressure fluctuations are much smaller than those of density and temperature. The approximated dispersion ratio is $\omega = \omega_B \cos\alpha$, where α is the phase velocity horizontal angle, and ω_B is the Brunt frequency (Grossard and Hook, 1978). The corresponding B-period at balloon altitudes is 4.8 min in mid-latitudes and 4.5 min in the tropics.

Variability of t, and hence of I, will be maximum in the direction along the wave phase plane. Therefore, if the gamma-telescope axis orients to the zenith, as it did in our case, the observation would give predominently QPV due to horizontal IGW with a period of about 5 min.

The ratio $\Delta\rho/\rho \sim \sqrt{\rho}$ holds for the isothermal atmosphere, from where gamma-ray intensity has to change as $\Delta I_\gamma/I_\gamma = \Delta t/t = \beta(\Delta\rho/\rho)_{z_0}$, where $\beta = 2$, which implies that QPV relative amplitude is twice as high as that of density variations at altitude z_0. For the real atmosphere $I < \beta < 2$ since short IGW undergo scattering at the altitudes between 30 and 50 km (and at altitude of 110 km) due to a high temperature gradient involved. This effect reduces QPV amplitude and at the same time provides conditions for superdistant waveguiding propagation of short IGW (Dikii, 1969) and, hence, increases the chance of their observation.

The fact that no marked variations of the charged component intensity (I_c) have been recorded seems natural in the frame of IGW explanation because of a weak altitude dependence of $I_c(z)$ which makes that $\Delta I_c/I_c \ll \Delta t/t$. Some modulation effects due to IGW must, however, be observable in the secondary charged component which is really the case (Komoda *et al.*, 1975).

The QPV–IGW association may suggest an explanation for the origin of IGW at altitudes of 30–40 km in the Earth's atmosphere. The observations provide that IGW are generated with periods of 5 min, 12–15 min, and 23–26 min while the theory of IGW propagation in the real atmosphere predicts only a B-period of about 5 min. On the other hand, the coincidence of QPV periods with those of solar oscillations (Hill *et al.*, 1978) has already been discussed and their common genetic origin has been postulated (Galper *et al.*, 1977) which strongly suggest the association of IGW of the Earth's atmosphere with short periodic solar oscillations. It is not yet known how the energy of solar oscillations reaches the Earth's atmosphere but it can be qualitatively postulated that the atmosphere of the Earth may experience resonant vibrations provoked by solar oscillations. These resonances can be most easily realized at radial global solar oscillations of low l-modes ($l = 0, 1, 2$). These modes of global solar oscillations with the period of about 5 min have been recently recorded (Grec *et al.*, 1980; Claverie *et al.*, 1979). Ultraviolet radiation with a wavelength ranging from 2400 to 2900 Å, which is known to undergo strong fluctuations (as compared with extremely weak ones in the optic rang) and is absorbed in the ozone layer, that is, practically at the same altitudes 30–40 km, may provide the mechanism of the solar oscillation propagation. The fact that during a solar eclipse atmospheric IGW has been detected with a period of 20 min speaks in favour of this hypothesis (Goodwin and Hobson, 1978). The assumptions made need experimental verification.

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