tion of the number of planes in the SST fleet or the effect of reducing the mole fraction of NO_x from the exhaust, it should be recognized that the steady-state concentration of O_3 depends on the square root of the catalytic ratio ρ. Thus a given situation is relatively slowly changed by further addition or reduction of NO_x. However, for small amounts of NO_x, there is a threshold effect, as seen from inspection of Eq. 6.

At least as late as April 1971, U.S. governmental agencies concerned with this problem (*30*) accepted two conclusions of the SCEP report: (i) NO_x from the SST would build up to mole fraction values between 6.8×10^{-9} and 6.8×10^{-8} in the stratosphere, and (ii) these amounts of NO_x "may be neglected." The purpose of this report is to point out that if concentrations of NO and NO_2 are increased in the stratosphere by the amounts accepted by the SCEP report and by governmental agencies, then there would be a major reduction in the O_3 shield (by about a factor of 2 even when allowance is made for less NO_x emission than SCEP used). However, the purpose of this report is not to say precisely by what factor the O_3 shield will be reduced by SST operation, but rather to point out that the variable (NO_x) that has been discounted is much more important than the variable (H_2O) that has been given so much attention. Just as the SCEP report incorrectly discounted NO_x and the SST planners for several years overlooked the catalytic potential of NO_x, it is quite possible (and, in fact, highly probable) that I have overlooked some factors, and the effect of NO_x on the O_3 shield may turn out to be less, or greater, than that indicated here.

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14 April 1971; revised 14 June 1971 ■

Apples in a Spacecraft

Abstract. *Some consequences of Newtonian mechanics, previously overlooked, result in a new understanding of the behavior of small bodies in the solar system. Collisions between such bodies lead not to a scattering of these bodies over an increasing volume but instead to a contraction resulting in a "jet stream," with application to meteor streams and streams of asteroids. It is possible that comets are formed by bunching in such streams.*

1) *Unperturbed motion.* Suppose that a number of particles ("apples") are enclosed in a spacecraft that is orbiting in a circle with radius r_0 around a central mass point M_c. Let us assume that the masses of the spacecraft and of the particles are so small that gravitational attraction between them is negligible.

I shall consider here the orbits of each particle around the central body (assuming that they will not be in permanent contact with the walls). Because the particles are confined in the cabin, they will collide (inelastically) with the walls until their orbital periods are all equal to the orbital period of the spacecraft:

$$T_0 = \frac{2\pi}{\omega_0} = 2\pi\mu_c^{-1/2}r_0^{3/2} \quad (1)$$

where ω_0 is the orbital angular velocity and $\mu_c = \kappa M_c$ (κ is the gravitational constant). This means that the orbits of all of the particles must have semimajor axes equal to r_0. The axes and the nodes may be differently oriented. Hence, when viewed from the spacecraft, the particles perform oscillations both in the axial and in the radial directions.

If we place an orthogonal coordinate system with the origin in the center of gravity of the spacecraft, the x-axis pointing away from the central mass, and the y-axis in the direction of motion, we can calculate the motion of a particle in the following way (*1*). If a particle is situated at a distance z from the x-y plane, it is acted upon by the z-component

$$f_z = -\mu_c z\, r_0^{-3} \quad (2)$$

of the gravitational attraction $\mu_c r_0^{-2}$ of the central body. Further, if it is located at a distance x from the y-z plane, its absolute angular velocity ω is inversely proportional to $(r_0 + x)^2$, which for the (relative) y-velocity in the rotating coordinate system gives approximately

$$v_y = (\omega - \omega_0)\, r_0 = -2\,\omega_0 x \quad (3)$$

The force f_x in the x-direction is composed of the gravitational force and the centrifugal force:

$$f_x = -\mu_c r^{-2} + r\omega^2 \quad (4)$$

where r is the disturbed distance to the central mass. Since the angular momentum

$$C = r^2\omega = (\mu_c r)^{1/2}$$

is constant, we have

$$r\omega^2 = C^2 r^{-3} = C^2 r_0^{-3}\left(1 - \frac{3x}{r_0}\right)$$

and

$$\mu_c r^{-2} = C^2 r_0^{-3}\left(1 - \frac{2x}{r_0}\right)$$

hence

$$f_x = -\mu_c x r_0^{-3} \quad (5)$$

Under the action of the forces described in Eqs. 2 and 5, the particles perform harmonic oscillations around the y-axis with the period

$$T = 2\pi(-f_x x^{-1})^{-1/2} = 2\pi\,\mu_c^{-1/2}\, r_0^{3/2}$$

which equals the orbital period (Eq. 1).

When oscillating, the particles may collide with each other and possibly also with the walls. We may assume that these collisions are at least partially inelastic, which means that the oscillations are damped. We may also assume that the cabin contains some gas to ensure that finally all oscillations are damped. (To simplify the discussion we may assume that the spacecraft has a synchronous axial rotation so that it always turns the same side toward the central body.)

When all oscillations are damped, all of the particles are situated on a straight line (the y-axis) through the center of gravity of the cabin, which points in the direction of motion. (To be exact, they are situated on a small arc of the circle r_0 along which the center of gravity moves.) Only by having this location can they orbit around the central body with the same period as the spacecraft and at the same time have no radial or axial oscillations.

In the Saturnian rings all particles are confined to the plane of motion, but there is a spread in the radial direction. This implies that particles at different distances from Saturn orbit with different periods. The space cabin, however, compels all particles to have

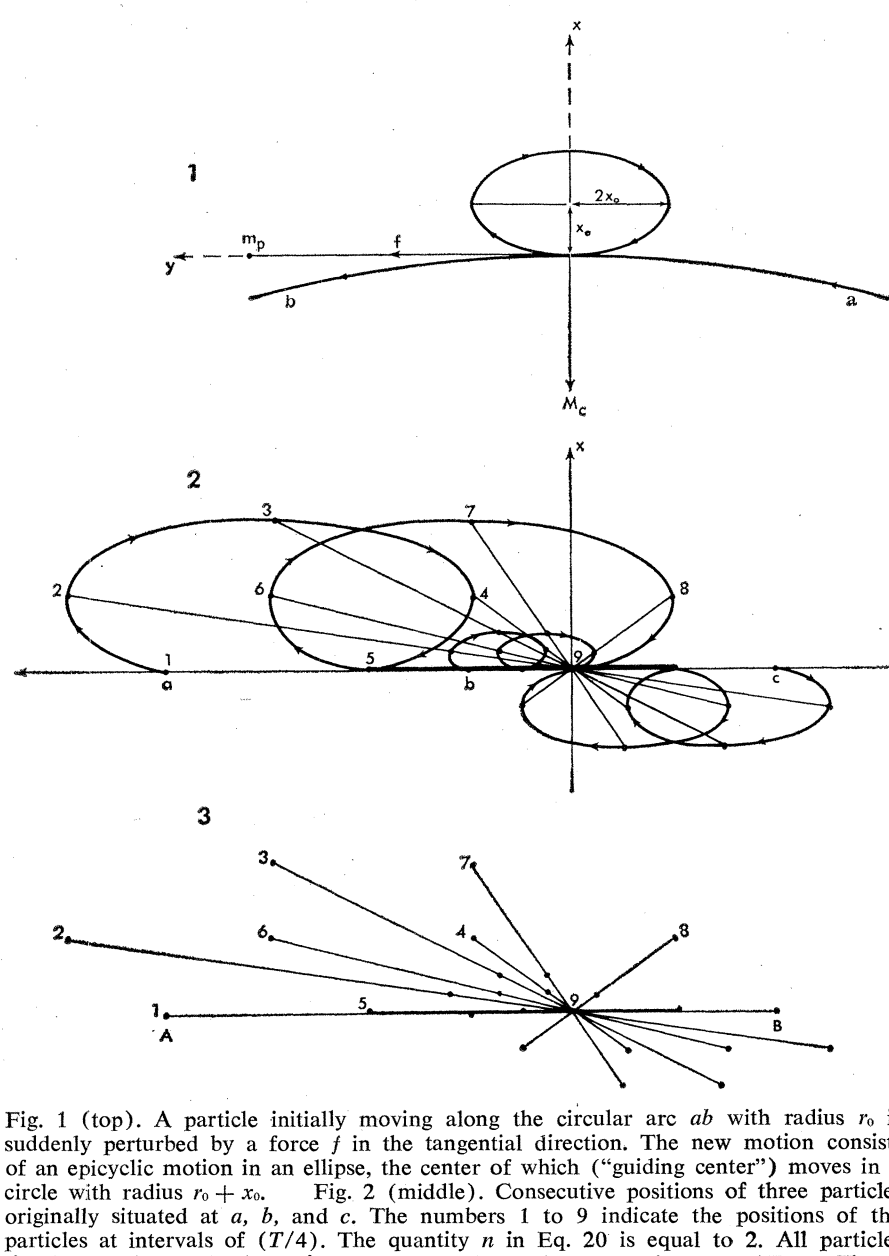

Fig. 1 (top). A particle initially moving along the circular arc ab with radius r_0 is suddenly perturbed by a force f in the tangential direction. The new motion consists of an epicyclic motion in an ellipse, the center of which ("guiding center") moves in a circle with radius $r_0 + x_0$. Fig. 2 (middle). Consecutive positions of three particles originally situated at a, b, and c. The numbers 1 to 9 indicate the positions of the particles at intervals of $(T/4)$. The quantity n in Eq. 20 is equal to 2. All particles simultaneously reach the point $x = 0$, $y = 0$ at the same time, $t = 2T$. Fig. 3 (bottom). The unperturbed particles form the line AB. The perturbation makes this line turn and first lengthen and then shorten. The figure refers to $n = 2$, in which case all the particles collide after two periods.

the same period, and hence the same orbital radius.

2) *Transverse apparent attraction.* As seen from the spacecraft, the behavior of the particles is the same as if they were subject to an apparent attraction $\mathbf{f}_a$ toward the y-axis:

$$\mathbf{f}_a = -\frac{\mu_c}{r_0^3}\rho \quad (6)$$

where

$$\rho = (x^2 + z^2)^{1/2} \quad (7)$$

The z-component of $\mathbf{f}_a$ is identical with the z-component of the gravitation of the central body. In contrast to this, the radial component of $\mathbf{f}_a$ is necessarily connected with a difference in the state of motion of the bodies. A displacement in the x-direction gives a harmonic oscillation in the x-direction and at the same time an oscillation in the y-direction. Equation 3 shows that the amplitude of the y-velocity is twice as large as that of the x-velocity. It is easily seen that there is a phase difference of $\pi/2$ between oscillations in the x-direction and those in the y-direction. Hence the particle moves in an "epicycle," that is, an ellipse with the length of the y-axis equal to twice the length of the x-axis.

3) *Perturbed motion.* Suppose that a particle with unit mass, which orbits in a circle with radius r_0 around a central mass point, is subject to the gravitational force

$$\mathbf{f}_p = -\frac{\mu_p}{\mathbf{r}_p^3}\mathbf{r}_p \quad (8)$$

of a small body $m_p \ll M_c$ situated in the x-y plane at a distance $\mathbf{r}_p$ from the origin of the moving coordinate system (xyz). We have put $\mu_p = \kappa m_p$. It is assumed that this force is applied during a short interval Δt $(\Delta t \ll T)$. It causes an increase in the specific angular momentum C of a particle by r_0 $(\mathbf{f}_p)_y$ Δt. The difference ΔC in the specific angular momentum of a particle at $(0, y_1)$ and a particle at the center of gravity of the spacecraft is given by

$$\Delta C = y_1 \frac{\partial}{\partial y}[r_0 (\mathbf{f}_p)_y]\,\Delta t = -\mu_p r_0 y_1 \frac{\partial}{\partial y}\frac{y}{(x^2+y^2)^{3/2}} = r_0 \Delta F \quad (9)$$

where

$$\Delta F = \mu_p y_1 \frac{3\sin^2\alpha - 1}{\mathbf{r}_p^3}\Delta t \quad (10)$$

and α is the angle between the x-axis and $\mathbf{r}_p$.

The new motion of the particle can be described as a circular motion of the guiding center superimposed on a motion in an epicycle (Fig. 1). The orbital radius of the guiding center is

$$r = r_0 + \Delta r$$

Putting

$$x_0 = 2r_0\frac{\Delta C}{C} = 2\frac{r_0^2}{C}\Delta F = \frac{T}{\pi}\Delta F \quad (11)$$

we have

$$\Delta r = x_0 \quad (12)$$

Since the position of the particle is not changed during the short interval Δt, the x-axis of the epicycle must be equal to x_0, and consequently the y-axis is equal to $2x_0$. The particle moves in the retrograde direction in the epicycle, and the center of the epicycle moves in a circle with the angular velocity $\omega + \Delta\omega$, where, because

$$\omega = C\,r^{-2} = \mu_c^2\,C^{-3}$$

$$\Delta\omega = -3\frac{\omega}{C}\Delta C = -\frac{3\,\Delta F}{r_0} \quad (13)$$

Hence after a time τ the guiding center will be displaced in the y-direction a distance

$$y_\tau = \tau r_0\,\Delta\omega = -3\,\Delta F\,\tau = -3\,\pi x_0\frac{\tau}{T} \quad (14)$$

in relation to an unperturbed particle.

To return to the problem discussed in sections 1 and 2, we want to calculate how the lined-up particles move in relation to the center of gravity of the spacecraft. Consider a particle situated at a distance y_1 from the center of gravity in the forward tangential direction. The velocity of its guiding center in relation to the center of gravity of the spacecraft is

$$v_y = r_0\,\Delta\omega$$

and, because of Eqs. 10 and 13, its displacement after a time τ is given by

$$y_\tau = -\frac{3\mu_p}{\mathbf{r}_p^3}\Delta t\,\tau\,(3\sin^2\alpha - 1)\,y_1 \quad (15)$$

Since

$$\mu_p = \kappa m_p$$

and

$$\kappa = 4\,\pi^2 T^{-2}\,r_0^3\,M_c^{-1}$$

we can write

$$y_\tau = -A y_1 \quad (16)$$

where

$$A = 12\,\pi^2\frac{m_p}{M_c}\left(\frac{r_0}{\mathbf{r}_p}\right)^3(3\sin^2\alpha - 1)\frac{\Delta t\,\tau}{T^2} = 3\,\pi\beta\frac{\tau}{T} \quad (17)$$

and

$$\beta = 4\pi\frac{m_p}{M_c}\left(\frac{r_0}{\mathbf{r}_p}\right)^3\frac{\Delta t}{T}\,(3\sin^2\alpha - 1) \quad (18)$$

Further, we find

$$x_0 = \beta y_1 \quad (19)$$

Hence we see that the state of motion produced by the perturbation ΔF is such that the y-values of all the guiding centers change in proportion to the original y-value of the particle (Fig. 2). We obtain $A = 1$ after a time $\tau = \tau_A$ which can be calculated from Eq. 17. At this moment all the guiding centers are on the same vector radius as the center of gravity of the spacecraft. The actual positions of the particles are scattered, however; all remain inside a square with its side equal to $4x_0$ and its center at the center of gravity of the spacecraft (Fig. 3).

A case of special interest occurs when

$$\tau_A = nT \quad (20)$$

where n is an integer. If this relation is satisfied, all the particles are back on their initial position of the epicycle. Hence, all particles are situated at the center of gravity of the spacecraft. The condition for this result is obtained from Eqs. 17 and 19:

$$\beta = \frac{1}{3\pi n} \quad (21)$$

or

$$12\pi\frac{m_p}{M_c}\left(\frac{r_0}{\mathbf{r}_p}\right)^3(3\sin^2\alpha - 1)\frac{\Delta t}{T} = \frac{1}{n} \quad (22)$$

If the perturbing body is situated in such a way that $3\sin^2\alpha > 1$ (which means that $\alpha > 35°$ or $\alpha < -35°$), we obtain a focusing of all particles to the origin.

From this treatment of this idealized case we may conclude that, if the motion of the spacecraft is subject to perturbing gravitational fields satisfying certain conditions, the row of particles has a tendency to contract toward the center of gravity of the spacecraft. Hence, in addition to the transverse focusing discussed in sections 1 and 2, there is also a longitudinal focusing. Under certain conditions, which need to be investigated in detail, all the particles in the cabin are collected at one point (the center of gravity of the spacecraft). The special case of Eq. 22 expresses this condition.

4) *Longitudinal apparent attraction.* In analogy with the transverse apparent attraction, the longitudinal focusing may be considered to be the result of

a longitudinal apparent attraction, although the type of motion produced by this attraction is rather different. Hence we find that under certain conditions the center of gravity of the spacecraft "attracts" all the particles in the cabin, in the sense that the particles have a tendency to be brought together here. (In the case of $-35° < \alpha < +35°$, there is instead an apparent repulsion by the center of gravity of the cabin.)

Because the spacecraft is assumed to have a negligible mass, one may ask why its center of gravity has such a remarkable property. The answer is that this point merely defines the state of motion of the whole assembly. Suppose that the mass of the spacecraft is much smaller than the mass of the particles and that their original common center of gravity were situated at an r larger than the center of gravity of the spacecraft. Then the particles would move more slowly than the spacecraft and would hit its backside wall, with the result that the spacecraft would be displaced outward so that its center of gravity would (almost) coincide with the center of gravity of the particles. (An exact statement is possible only if the original state of motion of the particles is known.)

The apparent attraction is more important than the Newtonian attraction between the bodies of mass m_1 under the condition

$$\mathbf{f}_a \gg \frac{\kappa m_1}{\rho^2} \qquad (23)$$

which means that

$$\frac{\rho}{r_0} \gg \left(\frac{m_1}{M_c}\right)^{1/3} \qquad (24)$$

For a spacecraft in orbit ($r_0 = 10^9$ cm) around the earth ($M_c = 6 \times 10^{27}$ g), particles with a mass of 6 g should be much more than 1 cm apart.

5) *Application to astrophysical problems.* I have treated a very simple model in order to clarify some aspects of celestial mechanics that have not attracted much attention so far. It is important to consider the extent to which similar phenomena may occur in astrophysics. The role of the spacecraft walls in our model is to compel all particles to orbit with the same period. However, this effect could also be achieved by other means, for example, by viscous effects, mutual collisions, and electromagnetic effects. There is a certain analogy between the lining up in the cabin of the particles, which originally are in random positions and have random velocities and the formation of jet streams of meteoroids or asteroids (*2*). The perturbation-produced focusing of these particles may be related to the formation of comets [see (*3*)].

It is also possible that my model may be applicable to some galactic phenomena. The general concentration of matter in the galactic plane is, of course, somewhat related to the phenomena I have studied, but it is possible that my model is also applicable to phenomena on a smaller scale. For example, the apparent attraction may keep a nebula together or make it contract even if the self-gravitation is insufficient for this contraction.

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26 April 1971

Rapidly Changing Radio Images

Abstract. *Differences in total transit time can give rise to images that expand at arbitrarily high speed. Two versions of a model based on this idea can account for the varying microwave structure reported for the quasar 3C 279. Other possible examples are suggested.*

Very-long-baseline interferometry is beginning to enable investigators to probe the spatial structure of the energetic cores of extragalactic sources, on the scale of light years. Since many of these sources are known to vary appreciably in microwave output over times of the order of 1 year, interpretation of the source structure will require full attention to retardation effects. It was pointed out a long time ago (*1, 2*) how these effects can give rise to kinematic illusions, that is, images (at arbitrary distance) whose apparent rate of change can far exceed c, the speed of light, even though no actual particle or signal velocity does so.

Recent measurements (*3*) suggest that such effects might be occurring in the quasar 3C 279; at a radio wavelength of 3.8 cm a fine structure is detected below 1×10^{-3} arc sec which shows definite changes over a 4-month interval. Because of the incomplete sampling, the interferometric pattern cannot yet be uniquely transformed into a spatial picture, but the simplest picture in accord with the measurements consists of two well-separated moving spots. The fluxes of the two spots are equal to better than 5 percent, and the spots move apart at a rate which—if the source is at the cosmological red-shift distance—is several times the speed of light.

The equal flux of the two moving spots in 3C 279 suggests that they are associated with a single physical source. Motivated by these findings, we present two versions of a kinematic model for rapidly moving double images associated with a single source (*4*). Observations of such patterns would not be surprising in any object that is variable over the time required for light to traverse the diameter, regardless of whether or not 3C 279 turns out to be a clear-cut example.

Model 1. Suppose an explosive event within the quasar sends out a sudden burst of energy in all directions, in the form of relativistic particles or of electromagnetic or other waves. Suppose further that a sharp increase in the radiation emitted at the observation frequency takes place when the primary pulse reaches a sphere of radius R, and that the increased emission is confined to a narrow shell (Fig. 1).

Under these conditions all parts of the shell brighten simultaneously; however, a distant observer receives the signal from each part at a different time, depending on its distance. Let $t = 0$ denote the instant when the brightening of the forward point A is first detected; then point B is seen to flare up at time

$$t = R(1 - \cos\theta)/c \qquad (1)$$

At first, the brightened region is a disk of diameter

$$D(t) = 2\,(2Rct - c^2t^2)^{1/2} \qquad (2)$$