# PHYSICS OF OUR DAYS

# Energy sources in quasars and nuclei of galaxies

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*Compact star cluster—Accreting black hole.—Supermassive magnetoplasma rotator.—Discussion.*

## INTRODUCTION

In the succession of brilliant astronomical discoveries of the last decades quasars and active galaxies occupy a very special position. Astrophysicists have been able to explain comparatively easily remarkable phenomena such as the three-degree microwave background (primordial radiation of the hot universe),[1] interstellar radio lines of exceptionally high brightness temperature (cosmic masers[2]), pulsars (rotating magnetized neutron stars[3,4]) x-ray sources (accreting neutron stars and possibly white dwarfs and black holes[5,6]), cosmic gamma bursts,[7] and also the x-ray bursts identified with globular clusters. Only the quasars and active nuclei of galaxies defy unambiguous interpretation—and already for many years now.

It is true that some years ago an important step was made in this direction: the data obtained by means of the largest telescopes shows that, as far as the nearest quasars are concerned, they are phenomena in the center of very massive ellipsoidal galaxies.[8,9] In addition, some quasars are found to occur in small groups and clusters of galaxies having the same (to within the usual velocity dispersion) red shifts as the corresponding quasars. As data accumulated, there was also revealed a deep qualitative similarity between the activity in quasars and the nuclei of nonquiescent galaxies (the so-called Seyfert, N, and radio galaxies[10]). These discoveries at least disposed of the suggested noncosmological nature of the quasar red shifts as well as the numerous and not infrequently fantastic hypotheses put forward to explain the activity of quasars on this assumption. But the mystery of the energy source was only intensified. The powers liberated in quasars if they are at cosmological distances are the highest known to physics. The total luminosity of quasars, which is variable in time, is as high for some of them as $10^{47}$–$10^{48}$ erg/sec, and a significant part to this energy is not in thermal form (the most primitive from the thermodynamic point of view) but in the highly organized form of the emission of relativistic particles in ordered magnetic fields. The rapidity with which the luminosity varies indicates that a gigantic power—$10^3$–$10^4$ times greater than the bolometric emission of all the stars of our Galaxy—is liberated in a volume with characteristic radius $R \lesssim 10^{15}$–$10^{16}$ cm, which only slightly exceeds the size of the solar system!

The gripping drama of the discovery of quasars, the variety of their properties compared with the similar manifestation of activity in the nuclei of galaxies, and also numerous hypotheses about the nature of the one and the other have been described in a number of reviews.[10–16] Although there have been no lack of hypothetical energy sources to explain quasar and galactic activity, only three can be regarded as possible: 1) compact star cluster; 2) accreting black hole; 3) supermassive magnetoplasma rotator. It is striking that new hypotheses about the nature of the activity which have appeared during the last seven to ten years in the wake of new observational data essentially reduce to one of these possibilities. The three types of source, which qualitatively satisfy the main requirements imposed by the observations—compactness, high and variable luminosity, more or less prolonged life—also have similar external parameters such as, for example, the mass and diameter. Therefore, a choice between these hypotheses is exceptionally difficult and it is possible only on the basis of a detailed and scrupulous comparison of their predictions (which are frequently also similar to one another) with the observational data.

It seems however that data on the optical variability of quasars and the nuclei of galaxies accumulated during the course of systematic many-year observations now permit one to restrict appreciably the number of conceivalbe possibilities. It has been found that a number of objects exhibit remarkable regularities in the variations of their light: these variations contain a component that is nearly periodic with a period $P_1$ of the order of tens or hundreds of days, and also a quasi-periodic component with a cycle duration $P_2$ of the order of several years (see Table I).

It is curious that the first indications of possible almost periodic variations of the light of some quasars were noted for the quasar 3C 273 immediately after its discovery; this was possible because of the valuable collection of photographic plates of its image taken over 80 years.[27] However, in the case of 3C 273, the light

TABLE I. Quasars and active galaxies with periodic and quasi-periodic variations of their light.

| Object | Classification | $P_1$, days | $P_2$, years | Literature |
|---|---|---|---|---|
| 3C 273 | Quasar | | 9±1.5 | 17 |
| 3C 345 | Quasar | 80.4 | 3 | 18,19 |
| 3C 446 | Quasar | 380 | | 20 |
| 3C 454.3 | Quasar | 339.6 | | 21 |
| 3C 371 | N galaxy | 169 | 5 | 22 |
| 3C 120 | N or Seyfert galaxy | 350 | 22.5 | 23 |
| NGC 4151 | Seyfert galaxy | 130 | 5.1 | 24,25 |
| NGC 1275 | Seyfert galaxy | 29.5 | 1.3 | 26 |

variations were found to be not completely periodic but rather quasiperiodic or cyclic because of phase drift.[17] Because of this comparatively complicated behavior of the light, combined with a more rapid variability, and the inadequacy of the methods of statistical evaluation used by the majority of investigators in this problem, the assertion in[17] of a quasiperiodic variation of the light and even the weaker assertion that the optical variability has a nonrandom character[28] provoked a discussion in the literature that extended over many years (see[29], which also contains references to earlier papers). But now it is hardly possible to doubt the regular nature of the light variations found in a number of sources and moreover by different groups of observers. It must be admitted though that it is still hard to judge to what extent all the periods $P_1$ are real and to what accuracy they are maintained, etc. If further accumulation of observational data on the variability of a given source shows that the signal-to-noise ratio for the chosen $P_1$ value increases, the final proof of its reality will have been obtained.

The regular variations in the light of the quasars and nuclei of galaxies can be used today as an effective means for choosing between the above possible sources of activity. Let us discuss the conclusions which can be reached by a detailed comparison[30] of the properties of these sources and the observed nature of the variability.

## COMPACT STAR CLUSTER

Two main mechanisms of energy release in a compact star cluster are known (see the reviews[14,15]). One of them corresponds to the late stage of evolution of a galactic nucleus, when collisions between stars become important. Depending on the ratio between the rms velocity $v$ of the stars and the parabolic velocity $v_p$ on the surface of a star, the stars either give off energy directly in collisions ($v \gg v_p$) or coalesce ($v \ll v_p$), forming a short-lived massive star, which then explodes like a supernova.

Since the collisions of the stars take place in a random and independent manner, the liberation of energy also takes the form of random uncorrelated pulses. There is a rigorous proof[28] that such pulses contradict the nonrandom nature of the light variations of 3C 273. It is clear that this model is even less capable of explaining the periodic and quasiperiodic variations of the objects listed in Table I.

In a different variant of the concept of a compact star cluster, the supernova explosions take place during the early evolutionary phase of the galactic nucleus, when the frequency of formation of young massive stars, which then explode as supernovae, could have been appreciably higher than the contemporary frequency.[1] If the explosions occur randomly and independently and are added *linearly* in the observed variations of the luminosity, this variant has the same difficulties as the first.

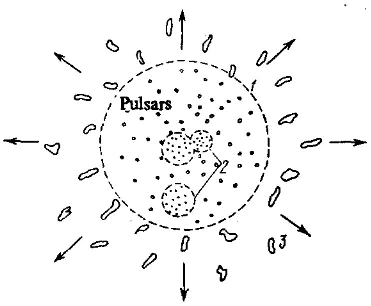

FIG. 1. Many-pulsar model of an active nucleus. 1) Boundary of region occupied by strong electromagnetic waves, relativistic particles, and high-frequency photons; 2) migrating zones of enhanced frequency of supernova explosions and predominance of young pulsars; 3) gas clouds—the products of supernova explosions.

These difficulties can be avoided by assuming that the individual independent pulses are not added linearly, i.e., the cluster of exploding stars has certain *collective* properties. Such a situation is proposed in the model of[31], according to which supernova explosions occur in a very compact active galactic nucleus with a frequency of 1–100 year$^{-1}$, leading to the formation of pulsars.[2] In this "many-pulsar model" (Fig. 1) neighboring supernova explosions merge and form zones of enhanced activity that migrate over the cluster and have certain collective properties. In such a system, one can attempt to explain the period $P_1$ and the quasiperiod $P_2$ by a combination of rotation and pulsations (more precisely, beats) of the cluster, which contains much plasma and a common magnetic field. The modulation of the radiation flux by the rotation must occur in this model through some anisotropy of the emission of the zone of enhanced activity. However, it is not clear how one can obtain such an anisotropy unless the pulsar axes are arranged in an ordered manner in space, which is implausible.[30]

The explanation in the framework of the many-pulsar model of the other properties of active galaxies and quasars presents numerous difficulties.[16] The complexity of this model, largely due to the arbitrariness in the choice of its main parameters, makes it hard to see how the difficulties can be removed or lessened.

## ACCRETING BLACK HOLE

The attractively simple idea here for the energy source in the nuclei of galaxies and quasars is that they contain supermassive black holes that "feed" on interstellar gas.[34] Under typical conditions, the gas falling into the hole, having angular momentum, forms a disk around it. Energy is dissipated from the disk through emission which peaks in the ultraviolet and optical ranges.[35]

The observed optical variations of the radiation flux from the nuclei of galaxies and quasars can be naturally attributed in the model of disk accretion to the exis-

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[1] Note that if phases of stormy star formation are repeated for some reason during the whole galactic history, an enhanced frequency of supernova formation need not necessarily be restricted to the early evolution of the galaxies.

[2] This model is a development of earlier work.[32,33]

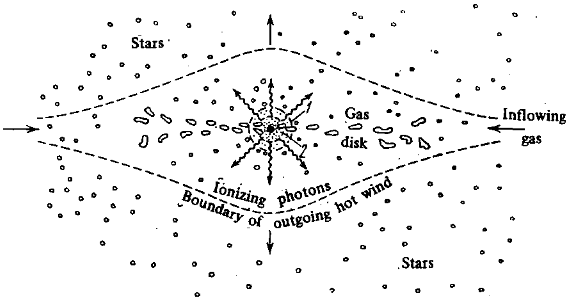

FIG. 2. Schematic structure of an active nucleus containing a supermassive accreting black hole. 1) Sphere of tidal breakup of stars; 2) corona around the black hole.

tence near the black hole of one or several inhomogeneities ("hot spots") rotating in Kepler orbits of gradually decreasing radius. However, this explanation encounters two difficulties.[30]

First, the radial drift of the hot spot leads to a shortening of the time interval between the light maximum and minimum and an increase in the amplitude of the variations. The observed variability of active nuclei and quasars does not exhibit intensifying "spasms" of this kind.

Second, the identification of the observed period $P_1 \sim 10^7$ sec with a Kepler period $\tau_K \sim (0.7\text{–}7)(M_h/M_\odot)$ sec of the region of maximal energy release having a radius of order 0.8–5 gravitational radii gives a black hole mass $M_h \sim (1\text{–}0.1)\cdot 10^{11} M_\odot$. However, it is known that the dynamics of the stars in the central regions of galaxies restricts the possible mass of a black hole to a much smaller value: $M_h \leq 10^8 M_\odot$. Consideration of the tidal breakup of stars in the neighborhood of a black hole makes it possible to reduce this upper limit further by several orders of magnitude.[36]

This difficulty can be avoided if the hot spot is at a distance $R \sim 10^2 R_g$ from the hole (where the rotation is much slower) and the gas surrounding the black hole is optically thick.[30] These conditions are satisfied by the modified model of an accreting black hole[37] shown in Fig. 2.

In this picture of accretion, which differs from the usual one, the observed quasiperiod $P_2 \sim 1\text{–}10$ years could also be explained by variations in the flux of gas that falls onto a black hole of mass $M_h \sim 3\cdot(10^5\text{–}10^6) M_\odot$.[3)]

The accretion onto the black hole may be due not only to interstellar gas which has escaped from evolved stars but also the tidal breakup of stars[34,38] that stray into the sphere of radius $R_t \approx 10^{11}(M_h/M_\odot)^{1/3}$ cm $\approx 10^{-2}(M_h/M_\odot)^{1/3}$ A. U. If the gas liberated by the tidal breakup of stars then moves around the black hole with the Kepler period, the period is $P \approx 9$ hours independently of $M_h$. A short and moreover universal quasiperiod of this kind has not been observed in quasars or the nuclei of Seyfert galaxies.[4)]

Thus, in the standard picture of disk accretion the observed regularities in the light variations of the quasars and active galaxies cannot be explained. In the more complicated model of an accreting black hole surrounded at a large distance from it by a thick layer of plasma the apparent difficulties are absent. The corona surrounding the black hole may contain a quasiregular magnetic field, in which locating and reconnection of magnetic lines of force could give rise to nonthermal flares.[40] However, the observable manifestations of such an object would be difficult to distinguish from those of an uncollapsed object, which we now consider.

## SUPERMASSIVE MAGNETOPLASMA ROTATOR

In one of the earliest attempts at explanation of the nature of quasars, Ginzburg pointed out[41] that during gravitational collapse the magnetic field may increase incredibly, and this could play an important role in transforming gravitational energy into the observed forms of activity of quasars and galactic nuclei. It is true that during the final stages of the collapse this field disappears,[42] but the actual idea that the magnetic field plays an important role remains fully valid for an equilibrium quasistationary plasma configuration formed during gravitational contraction. Such an object (a kind of supermassive star[43]) could be formed at a definite stage of evolution of a dense star cluster or be the product of accumulation in the galactic nucleus of gas lost during the evolution of stars. In the most general case, radiation, rotation, and the magnetic field contribute to the equilibrium; an object of this kind has been called a magnetoid.[44] Its structure and evolution for different types of rotation and geometry of the magnetic field were investigated in[45]. Below, we shall consider only the simplest realization of a magnetoid in the form of a supermassive inclined rotator with rigid-body rotation and quasidipole magnetic field. In the "cold" variant, such a rotator is identical with a "spinar" (giant pulsar).[46] However, the spinar model is not completely self-consistent, and preference must be given to the "hot" variant of a rotator, in which the thermal, rotational, and magnetic energy are all of the same order. The electrodynamics, evolution, and observational manifestations of such a rotator were considered in detail in[47] (see also the reviews[15,16]). The luminosity of the rotator is made up of thermal and nonthermal emission. The latter is due to losses of low-frequency ($\sim 10^{-6}$–$10^{-8}$ Hz) electromagnetic waves (magnetodipole emission) generated by the rotator during the secular deceleration of the rotation. The plasma which escapes from the rotator because of rotation-

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[3)] In the standard picture of disk accretion with this mass, one would expect a rapid irregular variability with characteristic time 3–30 sec. However, in the investigated nuclei of active galaxies the minimal characteristic time of increase of the light is $\Delta t \geq 1$ day.[26] In the modified model, the absence of such a rapid variability is naturally explained by the large optical thickness of the gas surrounding the black hole.

[4)] It is curious that a quasiperiod in the variations of the x-ray flux of about this duration is observed from the globular cluster NGC 6624, in which the presence of a black hole is suspected.[39]

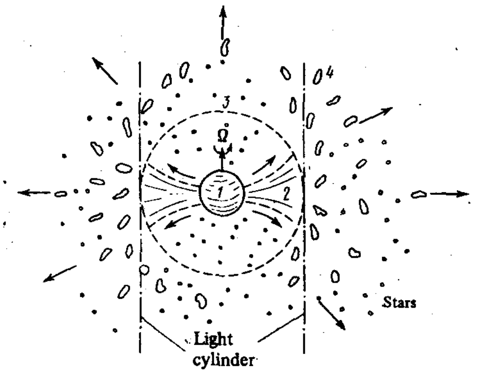

FIG. 3. Supermassive inclined rotator in an active nucleus. 1) Rotator; 2) plasma that flows outwards because of the rotational instability; 3) boundary of region occupied by low-frequency electromagnetic waves, relativistic particles, and high-frequency photons; 4) gas clouds accelerated by radiation and particles of the rotator.

al instability reaches the "light cylinder" ($r=c/\Omega$) in the form of two jets, after which it disperses and "envelops" the rotator (Fig. 3). The strong low-frequency electromagnetic wave is absorbed in the thin layer of this plasma and accelerates its particles to energies $\gamma=E/mc^2\sim 10^3$. The accelerated relativistic electrons emit in the magnetic field $H\sim 1$ Oe near the light cylinder predominantly at a frequency $\nu\approx 10^6 H\gamma^2$ Hz, which is in the submillimeter and infrared range. In this respect, as well as in many others, the supermassive inclined rotator as model of the energy source in active nuclei gives a good explanation of the main features of their nonthermal emission, which frequently lies predominantly in infrared peaks.

How can one explain the observed regularities in the optical variability of quasars and nuclei of galaxies?

The emission of the rotator is expected to vary periodically and quasiperiodically because of the rotation, pulsations, and intermittent nature of the outflow of matter (this last due to the competition between two mechanisms of angular momentum loss—escape of plasma and stretching of the magnetic lines of force joining the escaped mass to the rotator[47]). Analysis shows[30] that the observed regularities correspond qualitatively to what is expected: the period $P_1$ can be explained by the rotation of the rotator, and the quasiperiod $P_2$ by intermittent escape of matter from it. One obtains the following simple estimates for the main parameters of the rotator (mass $M$, radius $R$, strength $H$ of the poloidal magnetic field, and equatorial rotation velocity $v_e$) expressed in terms of the observed values of $p=P_1/800$ days and $q=P_2/10$ years:

$$M\approx p^{5/2}q^{-3/2}10^8\ M_\odot,\quad R\approx p^{3/2}q^{-1/2}10^{16}\ \text{cm};$$
$$H\approx p^{-1/2}q^{-1/2}10^6\,\text{Oe};\ v_e\approx p^{1/2}q^{-1/2}10^4\ \text{km/sec}.$$

The values of $P_1$ and $P_2$ taken from the table lead to very reasonable estimates for the parameters of the rotator as a source of energy of quasars and active nuclei. Such values of $M$, $R$, $H$, and $v_e$ guarantee both the necessary luminosity and the duration of the activity stage.[15,16]

## DISCUSSION

I have sketched above three possible sources of activity of quasars and galactic nuclei. The energy generation mechanisms in them are quite different. In a compact *star cluster* the energy release is ultimately due to either a collision and the breakup of stars (i.e., their *kinetic* energy) or is due to their coalescence, the rapid evolution of the resulting massive stars, and the resulting *nuclear* explosion. In addition to the nuclear energy release, an important role can be played here by the *rotational* energy of the pulsars—the remnants of the stellar explosions. In another conceivable source of activity—a supermassive magnetoplasma rotator (*magnetoid*) its *gravitational* energy is liberated through rotation and the magnetic field. The end stages in the life of a magnetoid may lead to its fragmentation and nuclear explosions. Finally, in the third source of activity—a *black hole*—gravitational energy is also released, this being liberated in the gas disk that surrounds the black hole and slowly settles (accretes) onto it.

Can one at this stage give a preference to any of these sources?

We have seen that the observed regularities in the variation of the optical emission of quasars and active nuclei of galaxies in principle provide a fairly effective means for selection from the existing hypotheses about the nature of the activity source. At the very least, some simple models can be rejected. These include a compact star cluster in which individual explosions that take place randomly and independently are added linearly. Only the more complicated model[31] in which the cluster of stars, which explode as supernovae and form pulsars, has collective properties that in some respects are like those of a single body can pretend to plausibility, although it already encounters a number of the difficulties mentioned above (see also[16]). It is also not known whether a cluster with the necessary parameters can be formed during the early stages of a galaxy or become one at an observed time.

At the least, we can establish that the model of activity of galactic nuclei and quasars in which stars explode randomly and independently cannot, at the very least, be applied to objects that exhibit a regular variability. We can assert that in such objects the energy source is a strongly bound system, and in the limit a single body. It remains to establish—and this is a very important but equally difficult problem—what is the nature of the body.

Consideration of the properties of such an object in a collapsed state (accreting black hole) has again shown that the *simplest* model of nonstationary accretion (hot spot on the surface of a disk) does not explain the observed regular variations in the light of quasars and galactic nuclei. A more complicated model containing an optically thick corona around the hole may be compatible with the observed variability. It is remarkable that the model of an accreting hole modified in this way has external properties rather reminiscent of a magnetoid—a rotating uncollapsed magnetoplasma object.

Even the simplest realization of a magnetoid in the form of a supermassive inclined rotator explains without apparent contradictions the observed regular variability of quasars and galactic nuclei: the period $P_1$ is due to the rotation of the rotator and the quasiperiod $P_2$ to the intermittent escape of matter from it.[5] The main parameters of the rotator obtained from the observed values of $P_1$ and $P_2$ are completely adequate to account for the energy of the sources and, provided there is a recurrent formation of rotators in the nuclei of galaxies, the necessary long duration of the state of activity.

Above, we have discussed the alternative energy sources in active nuclei only from the point of view of their compatibility with the regular nature of the observed variability. This has enabled us to conclude that the required source is not a cluster of randomly and independently exploding objects, but is some kind of single object. To solve the more detailed but nevertheless fundamental question of whether the source is a black hole or an uncollapsed object, it is necessary to consider the compatibility of these models with the complete set of observational data. Unfortunately, this is hindered by the insufficient development of the existing models (this applies particularly to accretion onto a black hole, the necessary modification of which has only been sketched above). Therefore, one cannot be sure that the successful explanation of the main properties of quasars and the nuclei of active galaxies in the framework of the magnetoid concept will not be reproduced (at least qualitatively) in the framework of accretion onto a black hole.

However, some of the properties of a magnetoid (in addition to the possibility of almost periodic modulation of its luminosity) are fairly specific and their observational confirmation would be decisive for preferring a magnetoid as the energy source. A justification for such a choice could be the following:

1) establishment of a nonthermal (synchrotron) nature of the observed infrared peaks;

2) proof of variability of the infrared continuum (including cyclic fluctuations of the luminosity with the same quasiperiod $P_2$ as in the optical range);

3) a large strength of the magnetic field over a region $10^{16}-10^{17}$ cm, which could be established by measurements of the polarization (especially circular) and Faraday rotation.

An interesting evolutionary test may be pointed out for the nuclei of Seyfert galaxies, which, besides strong emission, are characterized by a violent outflow of gas masses from their nuclei. Such outflow can be made possible by a black hole only if its luminosity $L$ is near the critical (the so-called Eddington) luminosity $L_E = 4\pi c G m_p M_h/\sigma_T = 1.3\times 10^{38}(M_h/M_\odot)$ erg/sec. If during the complete activity stage of the nucleus $L/L_E = \mathrm{const}$ (of course except for sporadic variations), then, during the accretion the mass of the black hole will, as is readily shown, increase in accordance with the law

$$M_h = M_0 \exp\left(\frac{t}{\tau}\right), \quad \tau = 0.45\cdot 10^9 \frac{\varepsilon}{1-\varepsilon}\frac{L_E}{L}\ \text{(years)},$$

where $\varepsilon = L/\dot{M}c^2$ is the efficiency of transformation of the accreted mass into radiation and $M_0$ is the initial mass of the black hole. As we have noted above, it follows from dynamical arguments that in the nuclei of galaxies $M_h < 10^8 M_\odot$ (this liberal estimate may be lowered further). Since $M_0 \geqslant (3-10)\cdot M_\odot$, we obtain $t/\tau < 17-16$. Invoking astrophysical arguments, we can assume that the time of existence of black holes in the nuclei of Seyfert galaxies is comparable with their age ($\sim 2\cdot 10^{10}$ years), i.e., $\tau > 1.2\times 10^9$ years. It follows directly from this that $L/L_E < 0.4\,\varepsilon/(1-\varepsilon)$, which even for the maximally possible $\varepsilon \sim 0.2$ is clearly insufficient ($L/L_E < 0.1$) to explain the observed powerful ejection of gas from the nuclei of Seyfert galaxies as an outflow from a black hole.

Of course, it is necessary to consider a more realistic situation than $L/L_E = \mathrm{const}$, although serious doubts about the concept of an accreting black hole as energy source in the nuclei of galaxies is confirmed by independent arguments, which restricts the mass of black holes in "quiescent" nuclei of galaxies (such as the nucleus of our own) to a very low value.[36]

This does not preclude the possible existence of relatively low-mass black holes not only in "quiescent" but also in active galactic nuclei (and in quasars). In active galactic nuclei and in quasars they could be conceived as a kind of hybrid with a much more massive magnetoplasma configuration, the leading role in the observed manifestations of activity evidently being played by the uncollapsed zone.[15,16]

Although a difficult path with successes and disappointments must be traveled before we arrive at a final understanding of the activity in quasars and galactive nuclei, the contours of the required energy sources are already becoming clearer. However, only further investigations will show to what extent this optimism is justified.

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[5] Note that if the magnetoid has three axes and the motion of its matter is not purely that of a rigid body (which is directly related to the role of the magnetic field) the period $P_1$ need not be strictly constant (see[30]).

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