TRNIL7901644

WIS-79/40-Ph

A Discussion of the Eccentric Binary Hypothesis for Transient X-Ray Sources.

II. Gradual Acceleration Stellar Wind Model.*

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* Research supported by the United States - Israel binational science foundation (BSF), Jerusalem.

Summary

We examine the eccentric binary hypothesis for transient x-ray sources in the framework of the gradual acceleration stellar wind model proposed by Barlow & Cohen. We find that a consideration of the ratio of maximum to minimum luminosities and of the ratio of the durations of the high and low states, for a typical transient x-ray source, yields a rather high eccentricity, despite the gradual acceleration of the wind. When typical physical parameters for the binary members are taken into account, we find that a consistent description is possible only for very eccentric orbits ($e \geq 0.9$), thus the model is inadequate as a general explanation of the x-ray transient phenomenon. We study the recurrent transient x-ray source 4U 1630-47, which was considered in the past to be a realization of the eccentric binary model, and demonstrate that it cannot be described consistently within the framework of the model, unless the optical primary is very peculiar.

Key words: transient x-ray sources, stellar wind, eccentric binaries,
accretion.

I. Introduction

Several authors (McCluskey & Kondo 1971; Tsygan 1975; Pacini & Shapiro 1975; Clark & Parkinson 1975) have suggested that the transient x-ray sources are in fact eccentric binary systems in which the accretion rate onto the compact star varies with the changing separation between the two stars.

The eccentric binary hypothesis has been analyzed by Avni, Fabian and Pringle (1976) (paper I) who found that the required eccentricities are close to unity, assuming mass transfer via a constant velocity stellar wind. Two approaches were used by these authors: the first involved the geometrical constraints imposed by the values of the "on time", the binary period, and the x-ray intensity modulation during the "on time". The second approach involved the physical parameters of a typical binary system in which the maximum x-ray intensity occurs at periastron. The eccentricities calculated in this way were even higher. As a representative example consider a transient x-ray source characterized by: $f = I_{x,max}/I_{x,min} = 100$ and $g = "t_{on}"/P = 0.1$. The geometrical approach yields $e = 0.93$ while the physical considerations imply $e = 0.97$. Since no regular recurrent transient was known to exist by then, the authors took $P \geq 2$ yr so that the calculated eccentricities represent in fact lower limits.

The eccentric binary model gained some support from observations of the recurrent transient x-ray source 4U 1630-47 (Jones et al. 1976; Kaluzienski & Holt 1977; Share et al. 1978; Kaluzienski et al. 1978), which was observed to flare quite regularly with a period of ~ 615 d.

Jones et al. (1976) analyzed the observations according to the geometrical approach of Avni et al. (1976), which gives $0.85 \gtrsim e \gtrsim 0.79$ (Jones et al. quote $0.85 \geq e \geq 0.65$). It turns out that by taking into account the physical considerations one gets $e \gtrsim 0.98$. This result is in a clear contradiction with the values imposed by the *geometrical considerations*.

The fact that the required eccentricities turn to be so high imposes a severe limitation on the model. The steady galactic x-ray sources have usually rather low eccentricities and there is no apriori reason that transient x-ray sources will not possess also intermediate values of eccentricity (see however Katz 1975).

As we show in section II the x-ray luminosity is roughly proportional to $V_\omega^{-4} r^{-2}$ (r is the distance between the stars and V_ω is the velocity of the stellar wind at the neutron star). Hence it seems apriori that much lower eccentricities may result if one relaxes the assumption of a constant velocity stellar wind, and allows V_ω to increase gradually with the distance from the optical star. Regarding the geometrical approach it seems that in this case a small variation in the separation will cause a sufficient change in V_ω, so that the required large intensity modulation will be achieved even for small eccentricities. Regarding the physical approach, a larger value of the required periastron distance and hence a smaller value of the eccentricity, are expected for a gradual acceleration stellar wind. In particular it was suggested by McCray (1977) that application of the velocity profile deduced by Barlow & Cohen (1977) from infrared observations of OBA supergiants will produce rather small eccentricities.

In the following we examine the general properties of the eccentric binary model, assuming the Barlow-Cohen velocity profile for the stellar wind; we also apply the analysis to the particular case of 4U 1630-47.

II. Mass transfer via a stellar wind

Let us consider an eccentric binary system in which the optical member loses mass through a stationary stellar wind. The continuity equation is

$$\dot{M}_p = 4 \pi \rho V_\omega r^2 \tag{1}$$

where $\dot{M}_p$ is the rate of mass loss from the primary optical star, r is the radial distance from its center and V_ω and ρ are the velocity and density of the wind at r. The rate of mass accretion onto the neutron star $\dot{M}_x$ is given by

$$\dot{M}_x = \pi r_a^2 V_{rel} \tag{2}$$

here V_{rel} is the wind velocity relative to the compact star and r_a is the accretion radius given by (Bondi & Hoyle 1944; Davidson & Ostriker 1973)

$$\frac{GM_x}{r_a} = \frac{1}{2} V_{rel}^2 \quad . \tag{3}$$

In eq. (3) it is assumed that the flow is supersonic which is indeed the case since the temperature in the wind is $\lesssim 10^6\ ^oK$ and $V_\omega \gtrsim 1000$ Kms^{-1}.

Combining eqs. (1), (2), (3) one obtains

$$\dot{M}_x = \dot{M}_p \frac{G^2 M_x^2}{r^2 V_\omega V_{rel}^3} \tag{4}$$

where r is the momentary orbital separation and V_ω, V_{rel} are evaluated at r.

Let us consider an eccentric binary system with eccentricity e and semi-major axis a. For the sake of simplicity consier the optical star to be non-rotating. In this case

$$V_{rel} = [(V_\omega - \dot{r})^2 + V_\theta^2]^{1/2} \tag{5}$$

where

$$r = \frac{a(1-e^2)}{1+e \cos \theta} \tag{6}$$

and

$$V_\theta = \sqrt{\frac{G(M_p+M_x)}{a}} \quad \frac{(1+e \cos \theta)}{(1-e^2)^{1/2}} \tag{7}$$

$$\dot{r} = \sqrt{\frac{G(M_p+M_x)}{a}} \quad \frac{e \sin \theta}{(1-e^2)^{1/2}} \tag{8}$$

The wind velocity as given by Barlow & Cohen (1977) is

$$V_\omega = V_\infty\, 10^{-1.74\, R_p/r}\, (1 - \frac{R_p}{r})^{0.21} \; . \qquad (9)$$

V_∞ is the terminal velocity, which we take to be $\approx$ 2.8 times the escape velocity from the surface of the primary (Lamers et al. 1976; Snow & Morton 1976), namely

$$V_\infty \approx 4 \sqrt{\frac{GM_p}{R_p}} \; . \qquad (10)$$

R_p is the radius of the star. Fig. 1 shows V_ω/V_∞ and is identical to the one in Barlow & Cohen (1977) except for a different choice of the independent variable. It is seen that the profile is indeed a very gradual one with $V_\omega(2R_p) \approx 0.12\ V_\infty$ and $V_\omega(7R_p) \approx 0.55\ V_\infty$.

Returning to eq. (4) and making use of eq. (10) one finds

$$\dot{M}_x = \frac{\dot{M}_p\ (\frac{M_x}{M_p})^2}{256(\frac{r}{R_p})^2\ \frac{V_\omega}{V_\infty}\ (\frac{V_{rel}}{V_\infty})^3} \; . \qquad (11)$$

Finally, the x-ray luminosity is calculated by assuming conversion of the gravitational potential energy of the mass striking the neutron star's surface into x-ray radiation.

$$L_x = \frac{GM_x}{c^2\ R_x}\ \dot{M}_x\, c^2 \qquad (12)$$

where R_x is the radius of the neutron star. It is common to all neutron star models that as M_x increases R_x decreases. if one assumes an equation of state of a non relativistic degenerate Fermi gas one has

$R_x \propto M_x^{-1/3}$ (Landau & Lifshitz 1958), so that

$$\frac{GM_x}{c^2 R_x} \approx 0.1 \left(\frac{M_x}{M_\odot}\right)^{4/3} , \tag{13}$$

and finally

$$L_y = 2.2 \quad 10^{38} \left(\frac{M_x}{M_p}\right)^2 \left(\frac{M_x}{M_\odot}\right)^{4/3} \left(\frac{\dot{M}_p}{10^{-5} M_\odot yr^{-1}}\right) \frac{1}{\left(\frac{r}{R_p}\right)^2 \frac{V_\omega}{V_\infty} \left(\frac{V_{rel}}{V_\infty}\right)^3} \mathrm{ergs}^{-1}, \tag{14}$$

III. Geometrical considerations

Since V_ω decreases as r decreases and since L_x depends strongly on V_ω one would expect that for a gradual acceleration wind, smaller changes in r (hence a smaller eccentricity) are needed to produce a given modulation in the x-ray intensity, compared to the case of a constant wind velocity.

In order to investigate quantitatively this possibility, we calculate numerically the quantity

$$y = (r/R_p)^2 \frac{V_\omega}{V_\infty} \left(\frac{V_{rel}}{V_\infty}\right)^3 \tag{15}$$

which appears in eq. (14), as a function of the orbital phase. Using eqs. (5) - (10) y can be expressed as a function of the orbital phase with the eccentricity and the dimensionless periastron distance $r_{p.a.}/R_p$ serving as parameters.

L_x changes as a function of the orbital phase from some minimal value $L_{x,min}$ to $L_{x,max}$ and then again to $L_{x,min}$. The modulation parameter is defined to be $f = \frac{L_{x,max}}{L_{x,min}}$ and the relative duration g is defined by $g = \frac{"t_{on}"}{p}$ where "t_{on}" is the time for which $L_x \geq L_{x,min}$. The results of the calculations are demonstrated in Figs. 2 and 3. Unlike in the case of a constant wind velocity (Avni et al. 1976) f and g do not specify uniquely the eccentricity but rather determine a range of eccentricities parametrized by different values of the dimensionless periastron distance. The solid curves in Fig. 2 show e vs. $\frac{r_{p.a.}}{R_p}$ for different values of g and a fixed value of f = 100. Fig. 3 presents the results for f = 30. The curves are plotted for $\frac{r_{p.a.}}{R_p} \gtrsim 1.5$ since for a closer approach the simple model of stellar wind accretion does not apply. For large values of $\frac{r_{p.a.}}{R_p}$, e tends to the value predicted by the constant wind velocity calculations of Avni et al. (1976). This is natural since $V_\omega \rightarrow V_\infty$ for large values of $\frac{r_{p.a.}}{R_p}$. As expected, when $\frac{r_{p.a.}}{R_p}$ is lowered a decrease in e results; but surprisingly for $\frac{r_{p.a.}}{R_p} \lesssim 2 - 3$, e reaches a minimum and then increases for closer approach. This effect is caused by the orbital velocity components that become larger for smaller $\frac{r_{p.a.}}{R_p}$. For small enough values of $\frac{r_{p.a.}}{R_p}$, these components dominate the expression for V_{rel} (the relative velocity) and counterbalance the effect of the changing wind velocity. The reduction of e from its value at $\frac{r_{p.a.}}{R_p} \rightarrow \infty$ is larger for larger values of g. However even for g = 1 (not shown in the figures) the calculations yield $e \gtrsim 0.4$ for f = 100 and $e \gtrsim 0.3$ for f = 30; the corresponding values calculated by Avni et al. (1976) are 0.82 and 0.7 respectively.

In the case of a typical transient with $f = 100$ and $g = 0.1$ the minimal e is 0.78, which is lower than the value obtained in the case of a constant wind velocity ($e \gtrsim 0.93$), but is still high.

It should be noted that due to the presence of the orbital velocity components in the expression for V_{rel}, the light curve is assymetric with respect to the maximal L_x (∿10% prolonged for positive phases). The maximum itself occurs at a slightly later orbital phase (10^{-2} - 10^{-3}) than that of the periastron passage.

IV. Physical considerations

It is clear, according to eq. (14), that for a given value of $L_{x,max}$ one can allow for a larger periastron distance, hence for a smaller eccentricity, in the case of the gradual acceleration stellar wind, compared to the constant velocity case.

Let us consider the binary system to consist of an optical star which is a typical early-type supergiant with $M_p = 20M_\odot$ and $R_p = 20R_\odot$, and of a neutron star with $M_x \leq 2M_\odot$. Let the mass loss rate from the optical star be $\dot{M}_p \leq 10^{-5} M_\odot yr^{-1}$ (a rather high value) and assume conservatively $p = 4yr$. The eccentricity as a function of $\frac{r_{p.a.}}{R_p}$ is

$$e = 1 - \frac{r_{p.a.}}{a} = 1 - \frac{r_{p.a.}}{R_p}\,\frac{R_p}{a} \approx 1 - \frac{r_{p.a.}}{R_p}\,\frac{1}{76} \quad (16)$$

where we made use of the assumed values for the binary parameters. It is found on the basis of eq. (14) that in order to have $L_x \gtrsim 10^{36}$ ergs^{-1} with $\dot{M}_p \lesssim 10^{-5} M_\odot yr^{-1}$ one needs $\frac{r_{p.a.}}{R_p} \lesssim 7.3$.

The dashed curve in Fig. 2 is the plot of eq. (16) for $\frac{r_{p.a.}}{R_p} \leq 7.3$. If one considers periods $p \geq 4$yr the dashed area in Fig. 2 results. It follows that a consistent application of the eccentric binary model for typical physical parameters of the binary system necessiates $e \gtrsim 0.903$. What is perhaps even more important is the requirement $g \lesssim 0.05$. In the case of a constant velocity wind one gets (Avni et al. 1976) $e \gtrsim 0.97$; $g \lesssim 0.01$. It is seen that even the application of the extreme gradual profile of Barlow & Cohen (1977) cannot resolve the difficulties of the model.

V. 4U 1630-47

The most promising candidate for a realization of the eccentric binary model was perhaps the transient x-ray source 4U 1630-47 (Jones et al. 1976; Kaluzienski & Holt 1977; Share et al. 1978; Kaluzienski et al. 1978). Unlike other recurrent transient x-ray sources the flares accured with a remarkable regularity which was naturally interpreted by Jones et al. (1976) in terms of an orbital period of $\sim$ 615 d. These authors also analyzed the observations according to the geometrical approach of Avni et al. (1976). The parameters of the source were found to be $f=30$, $0.34 \gtrsim g \gtrsim 0.17$ (with $g \approx 0.2$ as a prefered value). Thus the resulting eccentricity in the case of a constant velocity wind is $0.85 \gtrsim e \gtrsim 0.79$.

There is now some evidence which casts doubt on this interpretation. At the end of May 1978 the source flared again (Sims & Watson 1978), only $\sim$ 6 months after the preceeding outburst. At least this last flare is inconsistent with the interpration of the period as being orbital. One can argue that this outburst may have arised because of some irregular increase in the rate of the mass loss from the optical star *and* has *nothing* to do with the previous regulary spaced flares, but if such irregularities are allowed for in the system, why not interpret the preceeding flares on the same basis? Another objection is connected with the optical observations of Grindlay (1977, 1978) of a possible optical companion. The brightest star in the x-ray error box was found to be a red star, and for any reasonable interstellar reddining it turns out to be a late type sub mainsequence star, which is typical to the galactic center population (the galactic coordinates of 4U 1630-47 are: $\ell=337^{\circ}$, $b=0.28^{\circ}$). If this star is indeed the optical counterpart of the x ray source then mass transfer cannot take place via a stellar wind (mass loss rates are very low for late type main sequence stars) but must involve e.g. Roche lobe overflow and a formation of an accretion disk. If this is indeed the case, then $r_{p.a.} \lesssim 1R_{\odot}$ and the semi major axis $a \approx 390\ R_{\odot}$ (with $p=615d$, $M_x=1M_{\odot}$, $M_p=1M_{\odot}$) so that $e \gtrsim 0.997$ which is extremely high.

We can show that the interpretation of *4U 1630-47 according* to the eccentric binary model has difficulties even <u>within</u> the framework of this model. The observations of Grindlay (1977, 1978) put a lower limit on the observed visual magnitude: $m_V \gtrsim 15.5$ mag. If the optical star is assigned the physical parameters mentioned in IV then $M_V \lesssim -4$ mag,

and taking into account an interstellar absorption $A_V/D \lesssim 2$ mag kpc^{-1}, one gets $D \gtrsim 3.5$ kpc. This distance implies a x-ray luminousity $L_x > 5.3 \cdot 10^{36}\ ergs^{-1}$ for the outbursts reported by Jones et al. (1976), while a value of $L_x \gtrsim 2.45 \cdot 10^{37}\ ergs^{-1}$ results for the recent outburst (Kaluzienski & Holt 1977). From the observations of the recent flare (Kaluzienski & Holt 1977; Share et al. 1978; Kaluzienski et al. 1978), we find $f \gtrsim 30$ and $g \approx 0.2$, in accord with the values adopted by Jones et al. (1976) for the previous flares.

A consideration of the physical parameters of this system makes it clear that it cannot be described consistently if a constant wind velocity is ussumed. In order to produce $L_x \gtrsim 5.8 \cdot 10^{36}$ erg s^{-1} the periastron distance must not exceed $\sim R_p$. For a typical optical star (see IV) it follows that $e \gtrsim 0.977$ in contradiction with $0.85 \gtrsim e \gtrsim 0.79$ obtained according to the geometrical consederations. Even if one allows for an exceptionally large optical star, with $R_p \gtrsim 80 \quad R_\odot$ (Snow & Morton 1976) one still finds $e \gtrsim 0.91$.

Let us analyze the observations in the framework of the Barlow-Cohen profile. The geometrical approach yields according to Fig. 3 $0.85 \gtrsim e \gtrsim 0.48$ for $0.34 \gtrsim g \gtrsim 0.17$. Considering the physical approach let us write the eccentricity as a function of $\frac{r_{p.a.}}{R_p}$

$$e = 1 - \frac{r_{p.a.}}{a} = 1 - \frac{r_{p.a.}}{R_p \; 43.5} \tag{17}$$

where we made use of the binary parameters. From eq. (14) it is found that $L_x \gtrsim 2.45 \cdot 10^{37}$ erg s^{-1}, with $\dot{M}_p \lesssim 10^{-5}$ $M_\odot$yr^{-1} necessiates $\frac{r_{p.a.}}{R_p}$ [illegible]. The permitted values of e are represented by the dashed [illegible] in fig. 3. We find $e \gtrsim 0.913$ in contradiction to the values [illegible] by the geometrical approach. One needs also $g \lesssim 0.02$, in conflict with the observed value $g \lesssim 0.17$. In the case of a non typical optical star with radius $R_p = 80 R_\odot$ the lower dashed curve results. In this case a consistent description is only marginally possible with $e \approx 0.65$ and $g \approx 0.17$.

VI. Discussion

The eccentric binary hypothesis for transient x-ray sources was examined in the framework of the gradual acceleration stellar wind profile proposed by Barlow & Cohen (1977). Contrary to prior expectations it was found that even in the case of such an extreme gradual wind profile the resulting eccentricities are quite high.

An application of the geometrical considerations for the typical transient parameters $f=100$, $g=0.1$ yielded $e \gtrsim 0.79$ which, though lower than the value of $e \geq 0.93$ obtained by Avni et al. (1976) in the case of a constant wind velocity, is still rather high. A further decrease in the eccentricity is prevented by the presence of the orbital velocity terms in the expression for the relative velocity. These terms become important for close approach and their effect is to counterbalance that of the change in the wind velocity.

Consideration of typical physical parameters for the binary members constrains the eccentricity to be even higher: $e \gtrsim 0.913$. When the physical considerations are combined together with the geometrical approach it is found that a consistent picture is possible only for $g \lesssim 0.05$ (in the case $f=100$). Thus the application of a gradual stellar wind does not resolve the difficulties of the eccentric binary model, as there is no a priory reason for all transient binary x-ray sources to possess such high eccentricities.

In section V we examined the recurrent transient x-ray source 4U 1630-47 which has been considered in the past to be a realization of the eccentric binary model. We presented general arguments against an orbital interpretation of the periodicity. Furthermore, if the observations are analyzed within the framework of the eccentric binary model we find: (a) No consistent description is possible if a constant velocity wind is considered. (b) In the case of the Barlow-Cohen wind profile no consistent description is possible if typical physical parameters for the binary members are assumed. (c) A marginally consistent description is possible in the latter case if the optical star is exceptionally large ($R_p \gtrsim 80\ R_\odot$).

It is of relevance to mention that recently Rappoport et al. (1978) revealed the binary nature of the recurrent transient x-ray source 4U 0115+63. The source is characterized by $e \gtrsim 0.34$; $p \gtrsim 24d$ while the time interval between the outbursts is $\sim$ 7 yr. It is clear that in this source there is no relation between the binary period and the repetition rate of the flares.

We conclude that the eccentric binary hypothesis is inadequate as a general explanation for the nature of the transient x-ray sources, even if a gradual acceleration stellar wind is considered. At most it might be applicable only to a small subclass of transient x-ray sources in which the eccentricity is high.

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Figure Captions

Fig. 1 Stellar wind velocity as a function of the dimensionless distance from the star according to Barlow & Cohen (1977).

Fig. 2 Solid lines: eccentricity vs. the dimensionless periastron distance for f=100 and different values of g.

Dashed region: domain permitted by the physical parameters of typical binary members ($P \geq$ 4yr).

Fig. 3 Solid lines: same as in Fig. 2 for f=30.

Dashed upper line: eccertricity vs. the dimensionless periastron distance for the physical parameters of 4U 1630-47.

Dashed lower line: same as the preceeding one but for $R_p = 80\ R_\odot$.

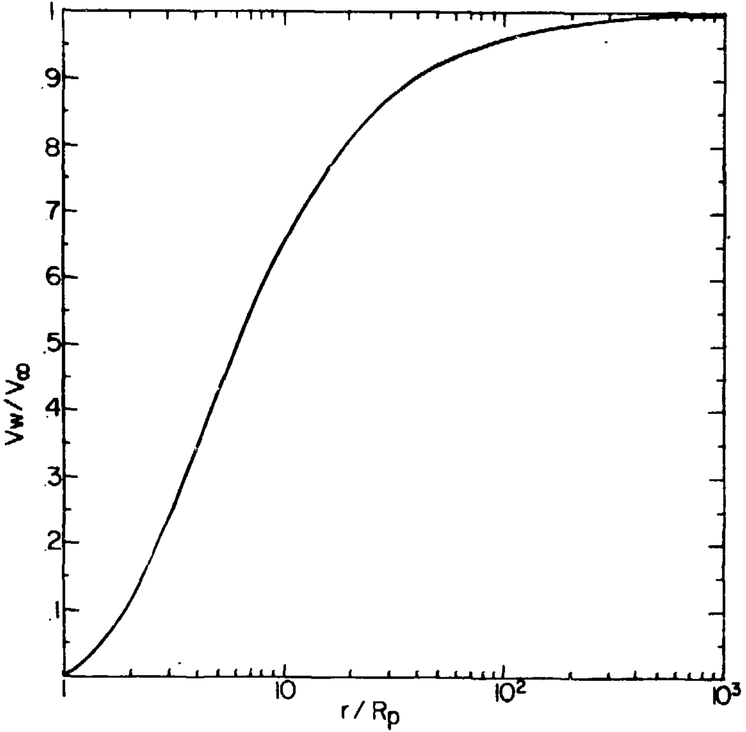
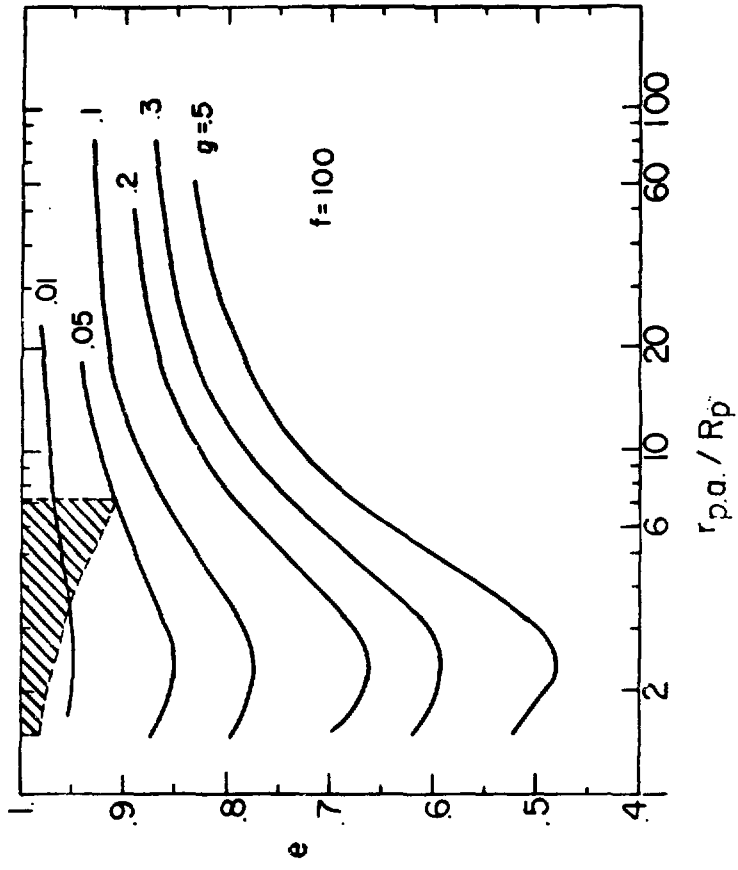


Fig. 1


e
1.
.9
.8
.7
.6
.5
.4
$r_{p.a.}/R_p$
2
6
10
20
60
100
f = 100
g = .5
.3
.2
.1
.05
.01

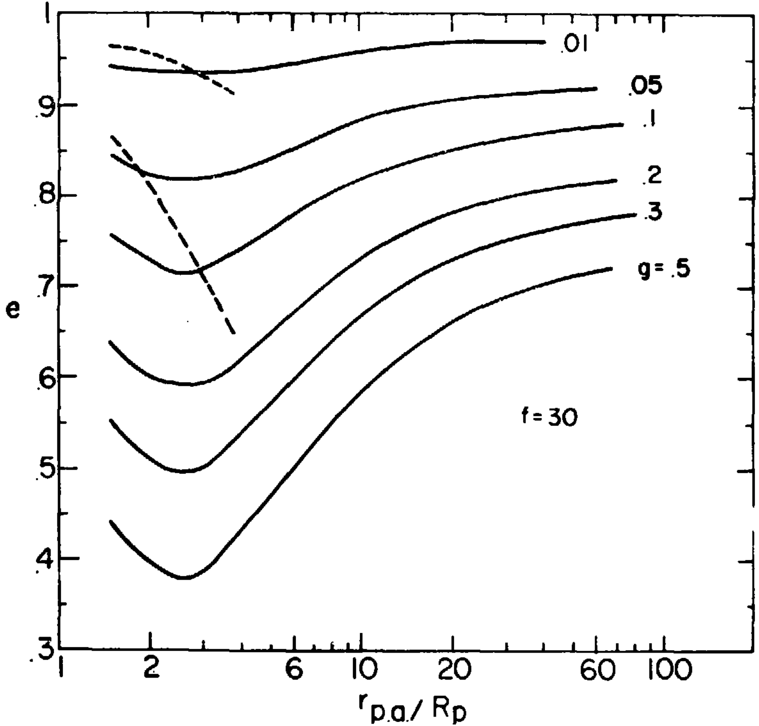


Fig. 3