Pancake detonation of stars by black holes in galactic nuclei

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ARTICLES

Pancake detonation of stars by black holes in galactic nuclei

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Recent efforts to understand exotic phenomena in galactic nuclei commonly postulate the presence of a massive black hole accreting gas produced by tidal or collisional disruption of stars. For black holes in the mass range 10^4–10^7 $M_\odot$, individual stars penetrating well inside the Roche radius will undergo compression to a short-lived pancake configuration very similar to that produced by a high velocity symmetric collision of the kind likely to occur in the neighbourhood of black holes in the higher mass range $\gtrsim 10^9$ $M_\odot$. Thermonuclear energy release ensuing in the more extreme events may be sufficient to modify substantially the working of the entire accretion process.

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MANY of the most plausible models for explaining spectacular energy release phenomena in galactic nuclei are based on the release of gravitational energy by gas accreting on to a very massive central black hole[1]. A likely mechanism[2] for providing the gas necessary to fuel such a model would be the breakup of ordinary stars, either by the Roche tidal effect in the case of a black hole with mass M below the Hills[3] limit, $M \lesssim 10^8$ $M_\odot$, or else by the effect of collisions in the case of a more massive black hole with a sufficiently dense surrounding star cluster. Gas release by tidal or collisional breakup (as well as by mechanisms such as supernovae and ordinary stellar winds) may also be important at other relatively quiescent stages in the history of a galactic nucleus containing a black hole, that is at times when the most observationally spectacular phenomena (such as quasars) are absent.

This article draws attention to a neglected effect which could be significant in many situations where tidal or collisional disruption occurs, namely that in the more extreme events (which may constitute a not negligible fraction of the total) the disruption will be preceded by a short-lived phase of high compression to a roughly pancake shaped configuration in which the density and temperature may rise enough to detonate effectively some significant fraction of the available thermonuclear fuel.

A very flat pancake type configuration will be formed briefly by any nearly head-on collision between roughly similar stars at very high relative velocities (analogous pancake formation being experimentally familiar in the microscopic context of very high energy proton–proton collision). We have in mind in particular the kind of event that is likely to occur near a black hole with the very large mass $M \gtrsim 10^9$ $M_\odot$ that is thought[4] to be necessary to account for the most extreme quasar phenomena. Beyond 0.1 pc from such an object, typical stellar collisions will have velocities $\gtrsim 10^4$ km s^{-1}, thus exceeding by a factor $\beta \gtrsim 10$ the minimum of the order of 10^3 km s^{-1} needed for disruption. Detailed studies of high velocity ($\gtrsim 10^4$ km s^{-1}) collisions will require an elaborate hydrodynamic treatment, with allowance for shocks, of the kind already available[5] for the intermediate velocity ($\approx 10^3$ km s^{-1}) collisions in which a moderate degree of flattening is already present. However, a preliminary idea of the effects to be expected may be obtained from consideration of the simpler but otherwise very similar configuration that arises during tidal disruption of a single star, whose evolution can be followed approximately[6,7] in terms only of ordinary differential equations using an adiabatic affine star model which, although highly idealized, can, nevertheless, be expected to provide a qualitatively valid description of the behaviour of the stellar core before, if not after the instant of maximum compression.

The phenomena of tidal disruption of a self gravitating body passing within the Roche radius

$$R_{\mathrm{R}} \approx M^{1/3} \rho_*^{-1/3} \qquad (1)$$

(where ρ_* is its characteristic central density) has been studied for over a century, but mainly in terms of an incompressible fluid model. It does not seem to have been realized that adequate allowance for compressibility leads to the prediction that a star penetrating deeply within the Roche radius will pass through a phase of compression to a highly flattened pancake configuration, closely similar, in both spatial and temporal characteristics, to that produced by a symmetric collision involving a pair of stars. It turns out that the effect of a collision with stellar velocities exceeding the central characteristic velocity (which is a few hundreds of km s^{-1} for a typical main sequence star) by a factor of the order of β can be roughly simulated by a single star following an orbit that penetrates to within a pericentre radius R_{p} given in order of magnitude by

$$\beta \approx R_{\mathrm{R}}/R_{\mathrm{p}} \qquad (2)$$

(a value β of the order of 10 thus being sufficient to reproduce the effect of a collision with relative velocity of the order of 10^4 km s^{-1}). Not only can the study of thermonuclear reactions in such a tidally produced pancake give a first rough indication of what may occur in a high velocity stellar collision, but it would also appear to be an astrophysically interesting phenomenon in its own right in the context of a black hole in the moderate mass range 10^4 $M_\odot$ to 10^7 $M_\odot$ for which it is possible to obtain a large value of β without the star either being penetrated by or swallowed by the black hole. The potential importance of this phenomenon stems from the fact that deep penetration is much less improbable than would be expected from purely geometric considerations. Just as the probability of high velocity collisions deep in the potential well of an $M \gtrsim 10^9$ $M_\odot$ black hole is enhanced far above what would be proportional to the corresponding volume (by an amount whose exact calculation is difficult) in consequence of the well known cusp effect in the stellar density distribution (see ref. 8), so, similarly, the probability of penetration of an individual star deep within the tidal field of a more moderate sized black hole will also be much higher than would be deduced from the corresponding purely geometrical cross-section, by an amount that can be relatively easily estimated from the characteristics of the individual approximately parabolic orbit. We conclude that the fraction of all tidally disrupted stars with penetration factor exceeding a given value β will be of the order of magnitude of β^{-1}.

Extent and duration of compression

To derive equation (2) it is sufficient to see that the tidal force on the star (which is inversely proportional to the cube of the radial distance R from the hole) will rapidly dominate the internal pressure and self-gravitational forces on the star as it begins to penetrate substantially within the Roche radius R_R (the latter being characterized by the condition that the tidal and internal forces have comparable magnitude). In these circumstances it will become a good approximation to treat the individual particles of the star as undergoing free fall in the external gravitational field on orbits of approximately parabolic form in planes all passing very nearly through the perihelion point on the centre of mass trajectory. These planes will be confined roughly within an angle

$$\alpha \approx R_*(R_p R_R)^{-1/2} \tag{3}$$

where R_* is the characteristic radius of the star in its approximately unperturbed state before passage across the Roche radius, as given in terms of the stellar mass M_* by

$$R_* \approx M_*^{1/3} \rho_*^{-1/3} \tag{4}$$

Thus in the centre of mass frame of the star the particles will effectively be accelerated towards the orbital plane, with maximum velocity, u say, of the order of αv where v is the orbital velocity at the pericentre, that is

$$u \approx \alpha\left(\frac{GM}{R_p}\right)^{1/2} \tag{5}$$

Hence we immediately see that the relative velocity u of what may be described as the collision of the star with itself will have the required form

$$u \approx \beta\left(\frac{GM_*}{R_*}\right)^{1/2} \tag{6}$$

where the factor $(GM_*/R_*)^{1/2}$ is interpretable as the characteristic velocity of sound in the core of the star.

When matter becomes sufficiently highly compressed, the free-fall treatment will, of course, cease to be valid: as the mass centre passes through the pericentre, the tidal forces, although high, will be overtaken by a very sharp last minute rise in the pressure forces, which will cause the star to bounce back towards a more isotropic configuration. Note that stellar deformation in directions in the plane of the orbit will not have had time to become important at the instant of passage through the pericentre (the 'tube of toothpaste' extrusion effect that is familiar from the incompressible case cannot have developed significantly at this stage) so the maximum degree of compression of the resulting pancake can be estimated directly from the requirement that the kinetic energy of the 'self-collision' be entirely converted into internal energy of the gas at the instant of turn around. If this energy is predominantly thermal, as will be the case in main sequence stars, the maximum central temperature Θ_m in the pancake will be given in terms of its value Θ_* in the unperturbed state of the star by

$$\Theta_m \approx \beta^2 \Theta_* \tag{7}$$

This formula will also be valid when the predominant internal energy is that of a non-relativistic degenerate electron gas, which scales proportionally to the non-degenerate thermal energy of the gas of positive ions. As long as the gas remains non-relativistic the corresponding maximum central density ρ_m will be given by

$$\rho_m \approx \beta^3 \rho_* \tag{8}$$

and the duration τ_m of the phase of maximum compression will be given by

$$\tau_m \approx \beta^{-4} (G\rho_*)^{-1/2} \tag{9}$$

where $(G\rho_*)^{-1/2}$ is the free-fall time scale of the star (which is automatically the same as the orbital time scale at the Roche radius R_R) whose value is of the order of 10^3 s for small main sequence stars.

Although the above arguments are crude we have confirmed them (see Fig. 1) by explicit numerical integration of the equations of motion governing an affine star model (in which the constant density layers are treated as retaining an ellipsoidal form) which represents the simplest and most natural extension of the incompressible fluid model (on which most previous numerical studies of tidal forces have been based). While probably at least qualitatively adequate during the compressive phase, such a treatment can be expected to be invalidated during the phase of subsequent expansion by the effect of shocks, whose potential importance in the envelope (as opposed to the central regions with which we are concerned here) has been pointed out by Lidskii and Ozernoy[9], who seem to have been the first to appreciate the significance of the tidal field's initial tendency to cause compression.

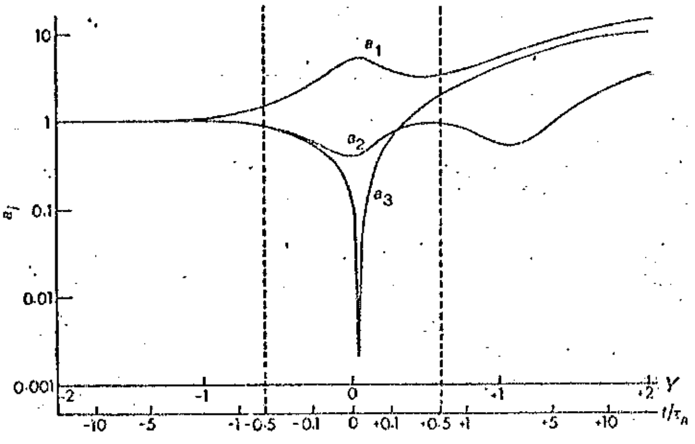

Fig. 1 The numerically calculated magnitudes of the principal axes a_1, a_2, a_3 (a_3 being orthogonal to the orbital plane) of a polytropic ($\gamma = 5/3$) affine (that is, ellipsoidally deformed) star model are plotted on a logarithmic scale as a function of the distance Y from the axis of a parabolic trajectory with Roche penetration factor $\beta = 10$. The corresponding time t, normalized as a fraction of the stellar oscillation time scale $\tau_R = (G\rho_*)^{-1/2}$, is indicated on a separate scale below, the approximate moments at which the star enters and leaves the Roche radius R_R being indicated by dotted lines.

Thermonuclear detonation

It is evident from equation (7) that a quite modest Roche penetration factor $\beta \approx 10$ can raise the temperature of a main sequence star from its usual value $\Theta_* \approx 10^7$ K to near the value $\Theta_m \approx 2 \times 10^9$ K at which (according to the standard formula given for example by Fowler *et al.*[10]) helium combustion by the triple-α reaction proceeds at a maximum rate for a given density, the relevant time scale being given (in c.g.s.) by

$$\tau_\alpha \approx 10^{11} (\rho_m X_\alpha)^{-2} \tag{10}$$

where the helium mass fraction X_α will have at least the cosmological value $X_\alpha \approx 1/4$. As the energy that can be obtained from helium combustion is only of the same order as the thermal energy (borrowed temporarily from the gravitational field) already present, the condition $\tau_\alpha \lesssim \tau_m$ is all that is required for a substantial fraction of this energy to be released. As the values $X_\alpha \approx 1/4$ and $\beta \approx 10$ lead roughly to $\tau_m/\tau_\alpha \approx 10^{-5} \rho_*^{3/2}$, we see that the efficiency of helium detonation depends primarily on the central density of the star, being reasonably high only when ρ_* approaches the order of 10^3 g cm^{-3}. By coincidence this is roughly the upper limit for main sequence central densities, being obtained near their lower mass limit, $M_* \approx 10^{-1} M_\odot$.

The foregoing leads us to conclude that the most favourable conditions for efficient helium detonation will occur in conceivably very numerous (see ref. 11) 'dark dwarf' stars that are just too small to reach the main sequence but which, nevertheless, maintain central temperatures $\gtrsim 10^6$ at densities ranging up to 10^3 g cm^{-3} during time scales of the order of 10^9 yr (see ref. 12). To reach $\Theta_m \approx 10^9$ K such a star needs perhaps twice as large a penetration factor β as in the main sequence case (with a correspondingly halved probability), but as a result

ρ_m will be raised from a main sequence maximum of the order of $10^6\,\mathrm{g\,cm^{-3}}$ to a value that can exceed $10^7\,\mathrm{g\,cm^{-3}}$. At such densities the degenerate electrons will enter the relativistic regime, so that equations (7)–(9) will need modification, but allowance for this seems to confirm the conclusion that τ_m/τ_α attains a value of the order of 1.

The carbon-12 formed in such a detonation process will immediately undergo further processing by α-capture and proton-capture reactions (whose details depend very sensitively on M_* and β) so that the total energy release may exceed the internal binding energy of the star by a factor of the order of 10^2. Thus instead of forming a diffuse cloud weakly bound to the black hole as in the non-violent disruption scenario described by Hills[3], the gas will be ultimately liberated from the star in the form of a cloud expanding at a rate far in excess of the velocity of escape from the black hole. Any discussion of detailed consequences is beyond the scope of this article. We mention only that the immediate effect of the pancake detonation will be to accelerate the matter orthogonally to the orbital plane, but that subsequent radioactive energy release may lead to slingshot ejection of a fraction of the matter at very high velocities in the direction opposite to that along which the star originally approaches the hole, and to the corresponding capture by the black hole of comparable fraction of the matter in very tightly bound cloud or disk, with thermal or orbital speeds $>10^4\,\mathrm{km\,s^{-1}}$. It is even conceivable that a self-sustaining hot C–N–O or rapid proton capture[13] hydrogen burning process may be set off in the expanding cloud, with even more spectacular consequences, but only a careful hydrodynamic treatment with adequate treatment of shocks will be able to check this. Analysis of the overall scenario resulting from interaction of gas from many disrupted stars will be even more complicated but we can conclude that the likely detonation of a fraction of the order of 1% (arising from say a 10% fraction with sufficiently high penetration factor β, of which a less easily estimable fraction, perhaps also of the order of 10%, may lie in the susceptible mass range) will probably be sufficient to modify significantly the overall energetics of the entire gas release process. (Analogous conclusions are probably valid for the more complicated situation resulting from collisional, as opposed to tidal, disruptions in the neighbourhood of much more massive black holes: the unfavourable statistical factor resulting from the probable necessity that both participants in the collision should lie in the susceptible mass range seems likely to be compensated by the enhanced probability of very high velocities due to the cusp effect.)

Although the triple-α reaction we have been considering provides the only opening for significant thermonuclear release from the compression of population II stars (consisting almost exclusively of hydrogen and helium) it has been drawn to our attention that if the stellar population in the galactic nucleus has composition similar to that of population I stars, such as the Sun, then energy release on an individually more modest scale, but in a much larger fraction of the disrupted stars, can result from C–N–O cycle reactions. It is not possible to carry through a complete C–N–O cycle during the short lifetime of the pancake configuration because some of the steps inevitably involve slow weak decays. Nevertheless, the first highly temperature sensitive proton-capture stages (together with the later disintegration of the products) can liberate several times the binding energy of a star of solar type, if the temperature in the pancake rises above a few times 10^8 K. As this effect is much less density sensitive and requires a lower Roche penetration factor ($\beta \approx 5$ would suffice) than the triple-α reaction, it will occur in a much larger fraction of the stars involved. Hence, although the individual events are much less spectacular, the total energy release from this process can (when averaged over all disrupted stars) provide a contribution to the overall energetics that is no less important than that arising from helium detonation. Indeed for a black hole near the Hills mass limit (where the larger penetration factors required for triple-α detonation are not possible) energy release from proton-capture will be the dominant contribution. The net effect will presumably be to convert the gas from the disrupted stars into an outgoing wind, leaving only a small fraction to be accreted by the hole.

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