Kinetically Dominated FRII Radio Sources

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ABSTRACT

The existence of FR II objects that are kinetically dominated, the jet kinetic luminosity, \( Q_t \), is larger than the total thermal luminosity (IR to X-ray) of the accretion flow, \( L_{bol} \), is of profound theoretical interest. Such objects are not expected in most theoretical models of the central engine of radio loud AGN. Thus, establishing such a class of objects is an important diagnostic for filtering through the myriad of theoretical possibilities. This paper attempts to establish a class of quasars that have existed in a state of kinetic dominance, \( R(t) \equiv Q(t)/L_{bol}(t) > 1 \), at some epoch, \( t \). It is argued that the 10 quasars in this article with a long term time average \( Q(t) \), \( \bar{Q} \), that exceed \( L_{Edd} \) are likely to have satisfied the condition \( R(t) > 1 \) either presently or in the past based on the rarity of \( L_{bol} > L_{Edd} \) quasars. Finally, the existence of these sources is discussed in the context of the theory of the central engine.

Key words: quasars: general — galaxies: jets — galaxies: active — accretion disks — black holes.

1 INTRODUCTION

The connection between accretion flow parameters and radio jet power is mysterious. Most quasars are radio quiet, however \( \approx 10 \% \) of optically selected quasars are radio loud and more importantly about \( 2 \% \) of quasars have powerful FRII radio lobes (deVries et al. 2006). The lobe emission is the signature that the time averaged jet kinetic luminosity, \( \bar{Q} \), is enormous, \( \bar{Q} > 10^{44} \text{ergs/sec} \) (Punsly 2001). It is not known how powerful the quasar jet can be relative to the thermal luminosity from accretion, \( L_{bol} \). Understanding the limits of jet power can help reveal the physical nature of the quasar central engine. The primary obstacle in this exercise is that in order for \( L_{bol} \) and \( Q \) to be estimated contemporaneously necessitates that \( Q(t) \) be derived from parsec scale radio jet observations and such efforts are plagued by poorly estimated Doppler enhancement factors (raised to the fourth power) and the results are often grossly inaccurate (Punsly 2005; Punsly and Tingay 2006). For example, the estimates of blazar jet power in (Celotti et al. 1997; Wang et al. 2004) indicate that \( R(t) \equiv Q(t)/L_{bol}(t) > 1 \) AGN are fairly common, but the results are skewed by poorly constrained Doppler factors (Punsly and Tingay 2005). Alternatively, the time averaged jet power \( \bar{Q} \) can be estimated more accurately from the isotropic properties of the extended emission. Some \( \bar{Q} > Q_{bol} > 1 \) sources were found in (Punsly and Tingay 2006). Unfortunately, the \( \bar{Q} \) estimate is not contemporaneous with the \( L_{bol} \) data, so one can not say if the sources presently satisfy or ever satisfied \( R(t) > 1 \). Grossly inaccurate measurements of \( Q \) are really of no value, so we must concentrate on the \( \bar{Q} \) estimates and combine this with other information in order to establish a class of \( R(t) > 1 \) sources. In section 3, a subsample of 10 FR II AGN with \( \bar{Q}_{Edd} \equiv \bar{Q}/L_{Edd} > 1 \), is argued to be comprised of \( R(t) > 1 \) sources.

2 ESTIMATION TECHNIQUES

In this section, we review the standard estimation techniques used in the following analysis. The more information that is known about the large scale radio structure such as the radio spectral index across the lobe and high resolution X-ray contours, the more sophisticated and presumably more accurate an estimate that can be obtained for the energy flux delivered to the lobes from the jet (Punsly 2005; Birzan et al. 2004; Punsly 2001). Unfortunately, such detailed information does not exist for most radio sources and we need an expedience that is helpful for studying large samples. Such a method that allows one to convert 151 MHz flux densities, \( F_{151} \) (measured in Jy), into estimates of \( \bar{Q} \) (measured in ergs/s), was developed in (Wilott et al. 1999; Blundell and Rawlings 2000), the result is captured by the formula derived in (Punsly 2003):

\[
\bar{Q} \approx 1.1 \times 10^{45} \left[ X^{1.1} Z^{2} F_{151} \right]^{2/3} \text{ergs/sec},
\]

\[ Z \equiv 3.31 - (3.65) \times \]
where $X \equiv 1 + z$, $F_{153}$ is the total optically thin flux density from the lobes (i.e., contributions from Doppler boosted jets or radio cores are removed). In this paper we adopt the following cosmological parameters: $H_0 = 70$ km/s/Mpc, $\Omega_\Lambda = 0.7$ and $\Omega_m = 0.3$. We define the radio spectral index, $\alpha$, as $F_\nu \propto \nu^{-\alpha}$. The formula is most accurate for large classical double radio sources, thus we do not consider sources with a linear size of less than 20 kpc. Alternatively, one can also use the independently derived isotropic estimator from Punsly and Tingay (2005) and a published example in which $(1985)$. More shortcomings of this method are discussed in Punsly and Tingay (2006) sample does not establish the $R(t) > 1$ condition. In subsection (3.1) it is argued that the $Q/L_{\text{bol}} > 1$ jets in table 1 satisfy $R(t) > 1$, for some $t$. The last three columns are $L_{\text{bol}}/L_{\text{bol}}$, $Q/L_{\text{bol}}$, $Q_{\text{bol}}$ and the references. If more than one observed frequency was available, a second estimate for $L_{\text{bol}}$ was provided for that source so that one can assess the error in using a composite SED to approximate $L_{\text{bol}}$. The QSO, 3C 455, requires some elaboration. This object has a narrow H$\beta$ (FWHM = 620 km/s), yet the nuclear luminosity is far stronger than a narrow line radio galaxy and its magnitude is more typical of a strong Seyfert 1 galaxy, hence its historical classification as a quasar. Implicit in the first estimate in table 1 is that the object is a narrow line Seyfert 1, but H$\beta$ appears weak compared to $[\text{OIII}]$ because $\lambda 5007$ (H$\beta$/[OIII])=0.2 and $\lambda 4959$+[OIII])=0.33 in narrow line Seyfert 1’s because the narrow line region is greatly enhanced by emission line gas that is excited by the jet and is aligned with the radio structure DeVries et al. (1999). In support of this interpretation, there is an elongated patch of diffuse emission enveloping the kpc radio jet axis between the two lowest contours of the HST image in Lehnert et al. (1999) with a flux approximately equal to the narrow line flux in the F702W filter Gelderman and Whittle (1994); DeVries et al. (1999). Alternatively, one can interpret the object as a narrow line radio galaxy and $M_{\text{bh}}$ can be estimated from the galactic host bulge luminosity. There are a variety of fits to the $M_{\text{bh}}$ - host bulge luminosity relation, but the fits of McClure and Dunlop (2002) offer the smallest scatter since they are based on large samples. The relation that is most relevant is the best fit estimator derived from 72 AGN in
experienced epochs in which being in a state of suppressed accretion. The most likely lifetime of the source. However, since

\[ \frac{L_{bol}}{L_{Edd}} < 1 \]

for all the broad line AGN. Furthermore, note that most of the QSOs in table 1 have prodigious accretion rates and \( R > 1 \) is not a consequence of the quasars being in a state of suppressed accretion. The most likely explanation of the data in table 1 is that these sources experienced epochs in which \( R(t) \sim 1 - 10 \) as opposed to the

alternative explanation that the broad line sources had protracted phases in which \( L_{bol}(t)/L_{Edd} \sim 1 - 10 \).

3.2 The Validity of the Estimates

Since the data set is small, the analysis of the data is particularly sensitive to the integrity of the estimates in table 1. The main drawback to the argument above is that the estimates of \( M_{bh} \) could be off by a large amount in an individual object. Furthermore, these sources appear to have \( \frac{Q_{Edd}}{L_{bol}} > 1 \) merely as a result of these errors. If this were the fundamental explanation of the \( \frac{Q_{Edd}}{L_{bol}} > 1 \) estimates then a statistical anomaly must also present, the 0.5 \( \leq \frac{Q_{Edd}}{L_{bol}} \leq 1.0 \) QSOs just below the threshold of table 1 never have \( M_{bh} \) over estimated (i.e. there are no false negatives for the criteria \( \frac{Q_{Edd}}{L_{bol}} > 1 \)). In subsection 3.2.3, it is shown that this anomalous requirement conflicts with the data used to create the virial mass estimates. Furthermore, there could also be errors of smaller magnitude associated with the estimates of 0.5 \( \leq \frac{Q_{Edd}}{L_{bol}} \leq 1.0 \) QSOs just below the threshold of table 1 never have \( M_{bh} \) over estimated (i.e. there are no false negatives for the criteria \( \frac{Q_{Edd}}{L_{bol}} > 1 \)).

Thus, we need to find \( M_R \) for the galactic bulge in order to utilize (8). The HST image is taken with the F702W filter and the apparent magnitude of the galactic bulge (after subtraction of the nuclear core and extended narrow line flux) is \( m_{702W} = 21.53 \) \cite{devries1992}. The \( m_{702W} \) magnitudes are approximately the Cousins R magnitudes. The transformation to the Cousins R magnitude along with the k-correction that is given in 0.46 \pm 0.03 \) \( M_R - (2.55 \pm 0.72) \) yields \( M_R = -21.5 \) and from (8), \( M_{bh} = 4.2 \times 10^7 M_{\odot} \). This is the basis for the second estimate in table 1.

3.1 Super Eddington Jets

A value of \( \frac{Q_{Edd}}{L_{bol}} > 1 \) suggests that even if the jet central engine is currently in a low state then at some epoch during the lifetime of the source it must have had \( R(t) > 1 \). For example, if PKS 1018-42 is not now nor has ever been kinetically dominated then the on average \( \overline{L_{bol}} > 1.45 \overline{L_{Edd}} \) for the lifetime of the source. However, since \( \overline{Q} = \int Q(t)dt \), the peak values of the instantaneous \( Q(t) \), \( \max [Q(t)] > 1.45 \overline{L_{Edd}} \). Thus, one expects that \( \max [L_{bol}] \) would have to exceed 1.45 \( \overline{L_{Edd}} \) by a significant amount at certain epochs in order for the PKS 1018-42 to have always been in an \( R(t) < 1 \) state. This is inconsistent with the magnitudes of the peaks in the duty cycle of quasar \( L_{bol}(t)/L_{Edd} \) based on our current knowledge, see 0.46 \pm 0.03 \) \( M_R - (2.55 \pm 0.72) \) yields \( M_R = -21.5 \) and from (8), \( M_{bh} = 4.2 \times 10^7 M_{\odot} \). This is the basis for the second estimate in table 1.

Furthermore, note that most of the QSOs in table 1 have prodigious accretion rates and \( R > 1 \) is not a consequence of the quasars being in a state of suppressed accretion. The most likely explanation of the data in table 1 is that these sources experienced epochs in which \( R(t) \sim 1 - 10 \) as opposed to the

The possibility of these types of errors in table 1 is dealt with by introducing as many different sets of observational data as possible in order to obtain independent estimates of the same quantities. Thus, any results that are way “out of family” like 26.7 for 3C 455 can be flagged as unreliable. In order to expose the largest potential source of error, \( M_{bh} \), is computed from as many different spectral bands and emission lines as possible (generally two entries in table 1). Similarly, we compute \( Q \) from two different estimators. Furthermore, we estimate all potentially reddened QSOs by 0.46 \pm 0.03 \) \( M_R - (2.55 \pm 0.72) \) yields \( M_R = -21.5 \) and from (8), \( M_{bh} = 4.2 \times 10^7 M_{\odot} \). This is the basis for the second estimate in table 1.

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Table 1. FR II Quasars with Super Eddington Jets

<table>
<thead>
<tr>
<th>Source</th>
<th>( z )</th>
<th>( Q )</th>
<th>( L_{bol} )</th>
<th>( \overline{R} )</th>
<th>freq</th>
<th>( L_{bol}/L_{Edd} )</th>
<th>( Q_{Edd} )</th>
<th>ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C 216</td>
<td>0.670</td>
<td>15.1/14.1</td>
<td>( \approx 0.12 )</td>
<td>( \approx 120 )</td>
<td>0.71/1.16</td>
<td>0.05 - 0.1</td>
<td>3.3 - 10</td>
<td>1</td>
</tr>
<tr>
<td>3C 455</td>
<td>0.543</td>
<td>7.13/5.04</td>
<td>0.38</td>
<td>18.7/13.3</td>
<td>0.94</td>
<td>1.42</td>
<td>26.7/18.9</td>
<td>2</td>
</tr>
<tr>
<td>3C 82</td>
<td>2.878</td>
<td>155.4/183.8</td>
<td>14.5</td>
<td>10.7/12.7</td>
<td>0.014</td>
<td>0.106</td>
<td>1.14/1.35</td>
<td>4</td>
</tr>
<tr>
<td>3C 9</td>
<td>2.009</td>
<td>148.3/174.8</td>
<td>25.0</td>
<td>6.22/7.35</td>
<td>1.67</td>
<td>0.264</td>
<td>1.57/1.85</td>
<td>5</td>
</tr>
<tr>
<td>PKS 1018-42</td>
<td>1.28</td>
<td>63.9/65.2</td>
<td>19.3</td>
<td>3.3/3.38</td>
<td>1.37</td>
<td>0.428</td>
<td>1.42/1.45</td>
<td>7</td>
</tr>
<tr>
<td>3C 14</td>
<td>0.871</td>
<td>73.5/87.0</td>
<td>14.7</td>
<td>4.35/4.45</td>
<td>1.37</td>
<td>0.326</td>
<td>1.42/1.45</td>
<td>7</td>
</tr>
<tr>
<td>4C 04.81</td>
<td>2.594</td>
<td>103.8/148</td>
<td>35.8</td>
<td>2.90/4.13</td>
<td>2.30</td>
<td>0.459</td>
<td>1.33/1.90</td>
<td>5</td>
</tr>
<tr>
<td>3C 196</td>
<td>0.871</td>
<td>73.5/87.0</td>
<td>14.7</td>
<td>4.35/4.45</td>
<td>1.37</td>
<td>0.326</td>
<td>1.42/1.45</td>
<td>7</td>
</tr>
<tr>
<td>3C 270.1</td>
<td>1.519</td>
<td>65.1/66.6</td>
<td>48.2</td>
<td>1.35/1.38</td>
<td>2.07</td>
<td>0.844</td>
<td>1.14/1.17</td>
<td>5</td>
</tr>
</tbody>
</table>
and the average values were then averaged for each source. This average, (1) and (3) are not accurate for linear sizes less than 20 kpc). Figure 1 is a histogram of the distribution of $Q_{Edd}$. Every effort was made to average away errant estimates. Every available broad line FWHM, Lawrence et al (1996); Brotherston et al (1994); Wills et al (1993); Aars et al (2003); Gu et al (2001); Marziani et al (2003); Barthel et al (1990); Kuraszkiewicz et al (2004), and continuum flux density, Lawrence et al (1996); Wills et al (1993); Aars et al (2003); Barthel et al (1990); Kuraszkiewicz et al (2004); Meisenheimer et al (2001); Simpson and Rawlings (2000), was gathered for each source from the literature and every combination of these was used to estimate numerous values of $M_{bh}$ from (5)-(7). These values were then averaged for each source. This average $M_{bh}$ and the average $Q$ from (1) and (3) were used to compute the "best estimate" of $Q_{Edd}$ for each source. These estimates were then assembled in the histogram of figure 1. This histogram shows that the $Q_{Edd} > 1$ QSOs are just the high end of a smooth distribution of $Q_{Edd}$ for the complete sample and are not outliers. Over 30% of the QSOs have $Q_{Edd} > 0.5$. This method of assigning $Q_{Edd} > 1$ to a QSO is very conservative. A single large estimate for $M_{bh}$ will swamp the other smaller $M_{bh}$ estimates and suppress the large $Q_{Edd}$ values (such as in 3C 196, 3C 190 and 3C 455). If one were to average the $Q_{Edd}$ values instead then large $M_{bh}$ would be suppressed and there would be four 3CRR QSO with $Q_{Edd} > 4$.

3.2.3 An Analysis of the Distribution of Errors

There are two major facts that allow a clear interpretation of the effect of the errors in the estimation techniques on the $Q_{Edd}$ of 1 QSOs in table 1 and figure 1, respectively. Firstly, the detailed investigation of 3C 216 in Punsly (2001) illustrates the existence of $Q_{Edd} > 1$ QSOs very convincingly. The $Q_{Edd} > 3.3$ condition in 3C 216 is verified by three independent estimators of $M_{bh}$, F(Hβ), F(Mg II), and the host bulge luminosity. Secondly, there is no evidence that the scatter in the best fit estimators is skewed asymmetrically to low values of $M_{bh}$ Vestergaard and Peterson (2000); Kong et al (2006). Comparisons to reverberation mapping based estimates indicate that the errors are symmetrically distributed about the best fit estimators, eg. figure 9 of Vestergaard and Peterson (2000). If not for these facts, one could take a pessimistic view and plausibly argue that the $Q_{Edd} > 1$ sources in table 1 and figure 1 are an artifact of selecting those sources in which the errors associated with the line width estimation techniques have underestimated $M_{bh}$. This argument implicitly assumes that the high end of the log($Q_{Edd}$) distribution represents the variance in the line width estimators, not the actual spread in $M_{bh}$. However, the example of 3C 216 demonstrates that $Q_{Edd} > 1$ sources exist, indicating that the more reasonable explanation of figure 1 is that the errors in the estimates are randomly distributed and they are not skewed preferentially to produce low $M_{bh}$. In particular, some of the sources with $Q_{Edd} > 1$ are probably actually, $Q_{Edd} < 1$ sources, but a similar number of the $0.5 < Q_{Edd} < 1$ sources are actually $Q_{Edd} > 1$ sources.

It is worth expanding the discussion of the $Q_{Edd} > 1$ sources beyond the most conservative of claims made above. This condition is far stronger than $Q(t)_{max} > Q_{Edd}$ and in general indicates episodic values of $Q(t)$ considerably in excess of $Q_{Edd}$. More realistically based on the discussion of section 3.1, all the sources that have $Q_{Edd} > 0.5$ almost certainly had episodes in which $Q_{Edd} > 1$ and the $R(t) > 1$ condition was satisfied. Considering that the median value in figure 1 is $Q_{Edd} = 0.26$, ~ 0.3 ~ 0.5 of the the 3C sources were likely to have been kinetically dominated at some time in their past. This claim can not be extended to the FR II population as a whole, but is a consequence of the fact that the 3C QSOs typically reside at the high end of the steep extended luminosity distribution for radio loud quasars.

4 DISCUSSION

The article demonstrates that many FR II sources are likely to exist in a state of $R(t) > 1$. The $Q_{Edd} > 1$ jets must satisfy $max[R(t)] > 1$, or else the accretion disks of the broad line AGN would episodically be in an un-physical state of $L_{bol}(t)/L_{Edd} < 1$. The Mid-IR 3C sample of Ogle et al (2003) indicated that ~ 1/2 of the FR II narrow line radio galaxies had no hidden quasar. Based on the discussion above, these are likely candidates to be in a state of $R(t) > 1$.

As a consequence of the near independence of the UV spectrum on the radio state, DeVries et al (2003); Corbin and Francis (1994), it has been argued that the black hole and not the accretion disk is the power source for FR II jets Semenov et al (2004). A large scale magnetic flux trapped within the central vortex of an accretion disk can produce relativistic jets, as seen in the MHD numerical simulations of Hawley and Krolik (2000); McKinney (2003); McKinney and Gammie (2004). Yet, as discussed in Punsly (2006), the errors might still persist and the potential effects are discussed in the following two subsections.

3.2.2 3CRR Quasars

One way to assess the role of the statistical scatter in the estimators is to study the complete 3CRR sample. We estimated $Q_{Edd}$ for every QSO > 20 kpc (remember, (1) and (3) are not accurate for linear sizes less than 20 kpc). Figure 1 is a histogram of the distribution of log($Q_{Edd}$). Every effort was made to average away errant estimates. Every available broad line FWHM, Lawrence et al (1996); Brotherston et al (1994); Wills et al (1993); Aars et al (2003); Gu et al (2001); Marziani et al (2003); Barthel et al (1990); Kuraszkiewicz et al (2004), and continuum flux density, Lawrence et al (1996); Wills et al (1993); Aars et al (2003); Barthel et al (1990); Kuraszkiewicz et al (2004); Meisenheimer et al (2001); Simpson and Rawlings (2000), was gathered for each source from the literature and every combination of these was used to estimate numerous values of $M_{bh}$ from (5)-(7). These values were then averaged for each source. This average $M_{bh}$ and the average $Q$ from (1) and (3) were used to compute the "best estimate" of $Q_{Edd}$ for each source. These estimates were then assembled in the histogram of figure 1. This histogram shows that the $Q_{Edd} > 1$ QSOs are just the high end of a smooth distribution of $Q_{Edd}$ for the complete sample and are not outliers. Over 30% of the QSOs have $Q_{Edd} > 0.5$. This method of assigning $Q_{Edd} > 1$ to a QSO is very conservative. A single large estimate for $M_{bh}$ will swamp the other smaller $M_{bh}$ estimates and suppress the large $Q_{Edd}$ values (such as in 3C 196, 3C 190 and 3C 455). If one were to average the $Q_{Edd}$ values instead then large $M_{bh}$ would be suppressed and there would be four 3CRR QSO with $Q_{Edd} > 4$. 

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these simulations are restricted to a maximum $R$
value, $R_{\text{max}} < 0.5$. The magnetic field line configuration
leading to a relativistic jet is created and maintained by
"pinning" the poloidal flux to the event horizon by a strong
accretion flow in conjunction with an incredibly massive and
unobserved enveloping wind that transports $>1M_\odot/\text{yr}$ of
relativistically hot protonic gas at $0.3c-0.4c$ for an FR II
quasar [Punsly 2007]. The black hole actually gains energy
over time due to the intense accretion flow (and associated
energy influx) required to compress a large magnetic flux
onto the small surface area of the event horizon. Thus, a jet
with large Q requires an intense accretion flow that will
radiate profusely for the radiative efficiency predicted in these
simulations, Beekwith et al. (2006), and $R_{\text{max}} \sim 0.1$.

Alternatively, the black hole energy extraction model of
Punsly (2001), and references therein that was numerically
realized in Semenov et al. (2004) is based on large scale mag-
netic flux that threads the equatorial plane of the ergosphere
(the active region) of a black hole [Penrose 1969]. The theo-
retical $Q$ values are 2 orders of magnitude larger than for flux
pinned on the event horizon because the surface area of the
equatorial plane in the ergosphere is
$pinned on the event horizon because the surface area of the
horizon that is threaded by magnetic
flux in simulations of Hawley and Krolik (2006); McKinney
(2004); McKinney and Gammie (2004) for rapidly spinning
black holes (parameterized by $a/M \approx 1$, where “a” is the
angular momentum per unit mass of the black hole in ge-
ometrized units), and the jet power scales like the surface
area squared [Semenov et al. 2004]. These solutions attain a
value, $R_{\text{max}}$, that was calculated in Punsly (2007),
\begin{equation}
R_{\text{max}} \approx 11 \frac{0.3}{\epsilon} (a/M)^{0.5} \cdot 0.90 < a/M < 0.99 ,
\end{equation}
where $\epsilon$ is the radiative efficiency of the accretion flow,
$L_{\text{bol}} = \epsilon (dM/dt)$ and $(dM/dt)$ is the accretion rate from
the disk to the black hole. The maximum efficiency from a thin
disk is $\epsilon \approx 0.3$ Novikov and Thorn (1973). For high $L_{\text{bol}}$
objects, luminous quasars, one expects $\epsilon$ to be near maximal
and $a/M \approx 1$ (see Bardeen 1970; Elvis et al. 2002),
thus $R_{\text{max}} \sim 10$ which would explain the high Q episodes
required to maintain a long term time average of $Q_{\text{edd}} > 1$.

These arguments seem to indicate that the essential
element that separates a radio quiet QSO from one that
launches a strong FR II jet with $R \sim 1$ is the for-
mation of strong vertical magnetic flux in the equatorial
plane of the ergosphere. This is prevented in the sim-
ulations of Hawley and Krolik (2006); McKinney (2005);
McKinney and Gammie (2004) as a very weak seed mag-
netic field is swept up in a single MHD fluid and compressed
onto the black hole. Alternatively, Spruit and Uzdensky
(2003) have investigated low angular momentum flux tubes
that evolve separately from the bulk of the MHD fluid. In
the two-fluid dynamics, the strong flux tubes “swim” relative to
the bulk MHD fluid and slowly move into the ergosphere.
This could be an essential piece of missing dynamics in the
present codes.

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