Energy Rate Density as a Technosignature: The Case for Stellivores

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Abstract
The energy rate density (ERD) metric is the central scientific measure underlying all of big history. It measures the rate at which free energy transits in a complex system of a given mass. How could it inform SETI and astrobiology? One simple way to proceed is to look for high ERD systems in the universe and binary systems in accretion are excellent candidates. I argue that these accreting binary systems might be instances of Type II stellar civilizations on Kardashev's scale, civilizations feeding on stars, or *stellivores*. I review living clues, such as their sheer variety, their existence far from thermodynamic equilibrium, the fine-tuning of their models, the existence of reserves, accretion and ejection control. I summarize these clues using living systems theory. I use known binary stars masses and accretion rates to compute the ERD of putative stellivores, such as cataclysmic variables (130), neutron stars (30) and transient black holes (19). The results support an anomalously high ERD. I discuss objections and counterarguments regarding the stellivore hypothesis, and implications for big history.

Keywords
SETI, astrobiology, high energy astrophysics, high energy astrobiology, energy rate density, technosignature, stellivore, binary stars, white dwarf, neutron stars, black holes, cataclysmic variables

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> *Biological complexification leads to* high energy, far-from-equilibrium systems*, rather than the lower energy, equilibrium systems that are the target of non-biological complexification, so in that fundamental sense the two are quite distinct.* (Pross 2005, 153–54)

The rise of Energy Rate Density (ERD) through cosmic evolution is the central theme of big history (e.g. Spier 1996; Chaisson 2001; Christian 2004). ERD measures the amount of energy that flows through a system, normalized by its mass. So, to have a high ERD a system must not only be able to sustain a high energy flow, it must also be of a relatively low-mass while surviving this high energy flow. For example, although the Sun has a high energy outflow, it is also very massive, and thus its ERD value is low, at about 2 $erg.s^{-1}.g^{-1}$ (Chaisson 2001, 139). By comparison, a human body has a value of about 2 x 10^4 and modern society 5 x 10^5 (Chaisson 2001, 139).

The strength and attractiveness of ERD lies in its literally universal applicability, because it only looks at matter and energy, so it can compare systems as diverse as galaxies, stars, planets, plants, animals, societies or technologies. Chaisson (2001; 2003; 2011) has argued at length that it can be used as a complexity metric, where the ERD has risen in cosmic evolution.

A natural application from this universality is that it would also apply to extraterrestrials we might find. This leads to a straightforward SETI search strategy. *The technosignature to look for are high energy rate density systems in the universe.* What are the known systems with high energy rate densities? We will show that binary star systems in accretion score anomalously high.

This direct argument invites us to seriously study binary systems in accretion in a new light, to evaluate if these could actually be complex, living, advanced civilizations. If so, they would constitute Type II civilizations on Kardashev's (1964) scale that are feeding on stars, or *stellivores* (Vidal 2014, chap. 9; Vidal 2016).

1 Living clues

Before computing ERDs of binaries in accretion, let us further motivate why we can suspect they may be complex or living, by reviewing some living clues.

1.1 Variety

The first thing a binary star astrophysics student learns is the "binary zoo" (for a popular level introduction, see Lipunov 1989). The zoo metaphor illustrates that there is a large diversity of accreting binary stars, and the novice can easily get lost (see table 1).

White Dwarfs (WDs)	**Neutron Stars (NSs)**	**Black Holes (BHs)**
Cataclysmic variables Novæ Dwarf novæ Z Cam stars SU UMa stars U Gem stars Recurrent novæ Nova-like variables VY SC stars UX UMa stars Magnetic Cataclysmic variables Polars Intermediate polars DQ Her stars Symbiotic stars	Accreting X-Ray Millisecond Pulsar (AXMSP) X-ray burster	Black Hole X-ray Binaries (BHXBs) Black hole transients (BHTs) Microquasars

Table 1. The variety of accreting binaries, classified according to the primary star (a dense WD, NS or BH). Binaries are also classified according to the mass of the companion star. If the companion has a low-mass, one speaks of a Low Mass X-Ray Binary (LMXB), and if it has a high mass, it is called a High Mass X-ray Binary (HMXB). As typical entries to the literature, for binary stars in general see (Hadith 2001; Eggleton 2006), for WDs, see (Warner 1995; Hellier 2001), and for accretion theory, covering NSs and BHs, see (Frank, King, and Raine 2002).

The phenomenology of binary stars is not only varied, it is also lively as it changes on human time scales (in milliseconds, seconds, minutes, hours, days, years or decades). This is remarkable because it is usually not the case in other astrophysical phenomena that vary more on timescales of millions of years. This may explain why binaries in accretion have been and still are attracting the attention of amateur and professional astronomers and astrophysicists. As our observations increase in resolution and width of wavelengths, models of accreting binary stars have become ever more sophisticated, subtle and varied. This stellar diversity and richness is reminiscent of the biological realm.

Binaries are often hard to model (e.g. Eggleton 2006, 254–56 lists 18 general problems). The phenomenology of a particular system can be so unique that it is common to see papers or series of papers dedicated to one single particular binary star system.

My point with these remarks about variety and difficulty of modeling is not to suggest any alien-of-the-gaps arguments: "if there is a phenomenon we cannot explain, then it's aliens" (see e.g. discussions in Wright et al. 2014; and Vidal 2019). Obviously,

one could list 200 anomalies or open problems, and we would still not have any proof of extraterrestrial life. More modestly, acknowledging enduring open issues, or enduring competing models to solve them justifies opening up the modeling space, also including astrobiological viewpoints. Once we have both astrobiological and astrophysical models, we can compare their qualities and shortcomings. But we first need to be motivated to construct astrobiological models, and this is a core objective of this paper.

Note that in a way, astrophysical models will never fail. Indeed, everything in the universe, whether it is living or not, can be described by physics. We could make a physics model of Albert Einstein by saying that he measured 172 cm. It would be a correct physical description, but we would be missing his biological, intellectual, political, and other human dimensions and subtleties.

Maybe astrophysics will continue its progress and explain all the phenomenology of accreting binary stars. Or maybe existing astrophysical models already contain ad hoc hypotheses and epicycles that would not be needed with astrobiological models. If astrobiological models become more predictive than astrophysical ones, we will be on the road towards a proof of extraterrestrial life.

1.2 Far from equilibrium

A generally agreed upon feature of life is its existence *far from thermodynamic equilibrium*. As Pross writes in the opening quote of this paper, high energy and far-from-equilibrium trend is the direction of biological complexification. In the stellivore interpretation, this insight implies that only a small subset of binary stars are candidate extraterrestrials. Kopal (1955) classifies binaries in three types: *detached binaries*, *semi-detached binaries*, and *contact binaries*. Detached binaries do not interact, and thus have no living features, while contact binaries are destined to merge towards equilibrium, which is not the direction of a living system. Only semi-detached binaries remain suspicious, where mass transfer occurs from one star to the other. One should also add the constraint that the system is open, i.e. that matter is ejected out of the gravitational pull of the binary system. In the astrophysics literature this is known as slow non-conservative processes (see e.g. Eggleton 2006).

Another closely related feature of living and complex systems is *homeostasis*, a capacity for remaining the same despite perturbations. Joël de Rosnay (1979) defined more precisely a homeostatic system as “an open system that maintains its structure and functions by means of a multiplicity of dynamic equilibriums rigorously controlled by interdependent regulation mechanisms.” In other words, when perturbed, complex systems are able to come back to their own equilibrium, while simple physical systems tend to come back to thermodynamic equilibrium.

A known problem in the physics of WDs is that the boundary layer temperature is constant (Mukai 2017 and references therein), a typical phenomenon of homeostasis. For example, Page et al. (2010) found that the accreting WD V2491 Cyg stabilized its temperature after an initial rise, while Zemko et al. (2015) found a similar temperature stable against orders of magnitude changes in luminosity.

1.3 Fine-Tuning

A consequence of homeostatic control is that living or complex systems have to maintain their state on a narrow range of parameters to sustain their organization. If they would deviate too much, they would get destroyed. This often results into fine-tuned parameters in models to account for the phenomenology of complex systems.

For example, the NS Aql X-1 doesn’t display pulsations, and yet has a strong magnetosphere. Patruno et al. (2018, 7b) conclude that “any magnetosphere around this system requires a strong fine tuning of the parameters to explain the lack of pulses”. In a stellivore interpretation, one could speculate that modulation of the strength of

magnetosphere would be expected, as it is an essential variable that can control others (e.g. the accretion rate).

Another example is in the formation of millisecond pulsars (MSPs). Smedley et al. (2017) have simulated the standard formation model and found that "the range of initial orbital periods required to produce the currently observed range of orbital periods of MSPs is extremely narrow". They do propose an alternative model that mitigates the issue, but it is beyond the scope of this paper and my expertise to evaluate it. In a stellivore interpretation, the standard evolutionary formation model may indeed be wrong, and other paths to form binaries need to be explored.

Here in particular, MSPs play the role of a timing and positioning standard for the galaxy, called the Pulsar Positioning System (PPS, see Vidal 2019 and references therein). If the PPS was engineered, the formation of MSPs would have a different history. For example, active MSPs would require serious cooling to function properly, and helium is an excellent coolant choice. This would be an alternative explanation why most MSPs are found accreting an helium WD.

1.4 Reserves

A key feature of life is the building of reserves before being used for maintenance or metabolic activity (see e.g. Kooijman 2009). The crucial role of reserves is also well-known in cybernetics and engineering. In the dynamics of accretion and ejection displayed by binaries, there is most often an accretion disk that stores temporarily the flux.

There is another less obvious buffering that exists through the observation of accreting NSs, namely that the "burst rate decreases for most sources with increasing $\dot{M}$ [accretion rate], despite the more rapid accumulation of fuel" (Galloway et al. 2008, 397a). This observation is indeed counterintuitive from a purely physical perspective, as one would expect bursts expelling matter out of the system to increase –and not decrease– as the accretion rate rises. This means that the fuel has to be stored, possibly in a controlled manner.

There is another independent argument showing that such storage happens, namely the fact that nuclear physics plays an important role in the phenomenology of NSs, while the gravitational energy released by accretion is about 40 times more efficient than fusion and should thus make nuclear reactions almost irrelevant. As Strohmayer & Bildsten (2006, 113) put it:

> if the accreted fuel was burned at the rate of accretion, any evidence of nuclear physics would be swamped by the light from released gravitational energy. The only way the nuclear energy can be seen is when the fuel is stored for a long period and then burns rapidly (as in Type I bursts and superbursts).

A third indication that there are reserves is that in many sources, the bursts are not frequent enough to burn all the accreted fuel (van Paradijs, Phenninx, and Lewin 1988; Zand et al. 2003). This have led to suggestions that another kind of slower nuclear burning is happening (see e.g. Revnivtsev et al. 2001; Bildsten 1995). In the stellivore interpretation, this might be a sign that some energy is also used internally for growth and maintenance or that controlled nuclear reactions are taking place.

1.5 Accretion Control

A high energy flow or high ERD is not a sufficient condition for life. The control of energy flow is equally essential for life. For example, whether a human would decide to eat non-stop or to stop eating completely, he would end up dying. So energy flow needs to be controlled to ensure the basic functions of growth, maintenance and

reproduction (see e.g. Aunger 2007; Chaisson 2011). In the stellivore context, the challenge is thus to find signs of *accretion control*. On a superficial level, it is already well-known and well-studied that accretion turns itself on and off in many binaries. More precisely there are really two kinds of accreting NSs or BHs, the *persistent* ones that accrete at a high rate and constitute about two third of known systems, and the remaining third are *transient* ones that have lower accretion rates (Tanaka and Shibazaki 1996). The transient ones are thus better stellivore candidates because they turn accretion on and off, although it is difficult to completely rule out the persistent ones as they may be persistent only for the time scale we have been observing them.

Let's take a closer look at how accretion turns itself on and off. In the case of magnetic WDs, it would make most sense to control accretion through magnetic field lines. For example, the accretion stream in Am Her star (AR Uma) displays a complex "transition from ballistic to magnetically controlled flow" (Hellier 2001, 111–12). One of the reasons of this complex transition is that the magnetic field is tilted, so that the streams flows preferentially follow this route. Hellier remarks that physical systems "tend to settle into their lowest-energy configuration, but diverting the stream out of the plane requires energy". We have again a far from equilibrium situation. As I suggested earlier (Vidal 2014, 240–41), in the stellivore interpretation, tilting the magnetic field would be a straightforward way to turn accretion on and off.

In the case of NSs, accretion rate can vary over 4 orders of magnitude (Lamb and Boutloukos 2008, 93). The accretion rate can be modulated via the accretion disk, or via a variation of the magnetic field's strength –that itself can vary over 4 orders of magnitude. For accretion control via an accretion disk, Bult et al. (2018 and references therein) suggest to account for recent observations of Alq X-1 by "an intrinsically variable accretion disk that propagates variability down to the power-law emitting region by modulating the mass accretion rate".

More generally "there is strong evidence that the external magnetic fields of neutron stars in LMXBs decrease by factors $\sim 10^2$ - 10^3 during their accretion phase perhaps on timescales as short as hundreds of years" (Lamb and Boutloukos 2008, 94). However, the magnetic field can also change on much shorter timescales, for example the system SAX J1748.9–2021 "was observed first as a non-pulsating atoll source (in 1998), then it turned into an intermittent AMXP [Accreting Millisecond X-ray Pulsar] (in 2001, 2005 and 2009 […], and then it became a persistent AMXP in 2015 […]. In this case therefore, the neutron star magnetosphere, if absent in 1998, must have re-emerged on a relatively short timescale for a reason that is not completely clear." (Patruno, Wette, and Messenger 2018, 7b).

To sum up, in the stellivore interpretation, lowering or tilting the magnetic field would allow accretion control. In the case of BHs, the dynamics is similar as with NSs, but the control might be interpreted via the different states of the BH accretion disk, which are known to correspond to different levels of accretion rate.

1.6 Ejection Control

For a living being or a society to prosper in the long run, disposing of waste is as critical as ingesting food or energy. So one should also look at traces of controlled ejection of waste materials in putative stellivores. Generally, WDs eject matter through *novae*, while NSs and BHs eject via *bursts* and *jets*.

In the case of accreting WDs, astrophysicists have found a "growing sample of novae which show evidence for complex, multi-phase ejection" (Chomiuk et al. 2014, see also references therein).

In NSs, double thermonuclear bursts (Type I) have been found. As Galloway et al. comment: (2008, 397a) "bursts with extremely short recurrence times (''double'' or ''prompt'' bursts) have long presented a challenge to our understanding of burst physics.

Their recurrence times of $\gtrsim$ 5 minutes are too short for sufficient fuel to accumulate to allow ignition by unstable thermonuclear burning". As Lewin et al. (1993, 254) comment, "these intervals are much too short to replenish, through accretion, a sufficient amount of nuclear fuel to account for the second burst. Thus, one requires the presence of a reservoir of nuclear fuel which survived the previous thermonuclear flash, and can be prematurely rekindled". In the stellivore interpretation, this is consistent with the idea of existing reserves, and being able to use just a part of them.

Even more intriguingly, in the three NS systems 4U 1636-536, 4U 1709-267 and SAX J1808.4-3658, it has been found that a weak burst *precedes* a normal burst by a few seconds only (Galloway et al. 2008, 397a). A similar behavior has also been observed with the WD system T CrB, about which Schaefer (2010) comments: "how can the turning off of accretion *anticipate* or *trigger* the nova event?". It is not clear how to interpret such a behavior, but anticipation is indeed a key hallmark of life, and we might be dealing with ejection control here.

1.7 Living system summary

To sum up the living cues we've reviewed, the framework of living system theory (J. G. Miller 1978; J. L. Miller 1990) is most useful (see also Vidal 2014, 239–48; Vidal 2016). As summarized in Table 1, J. G. Miller argue that all living systems have 20 subsystems performing different critical functions (the 20th timer subsystem was added later by J.L. Miller).

Matter + Energy + Information	**Matter + Energy**	**Information**
1. Reproducer	3. Ingestor	11. Input transducer
2. Boundary	4. Distributor	12. Internal transducer
	5. Converter	13. Channel and net
	6. Producer	14. Decoder
	7. Matter-energy storage	15. Associator
	8. Extruder	16. Memory
	9. Motor	17. Decider
	10. Supporter	18. Encoder
		19. Output transducer
		20. Timer

Table 1. Twenty living subsystems proposed by J.G. and J.L. Miller. They are classified according to their use of matter, energy and information (left column), matter and energy (central column), or information (right column).

In the stellivore interpretation, the *reproducer* subsystem is the most speculative one, yet arguably the most fundamental. Stellivores would be tackling the ultimate issue any intelligence in the universe has to face: to find a solution to the heat death of the universe. One way out would be to make a new offspring universe and would certainly require enormous amounts of energy (see Vidal 2014 for a book-length case of this scenario and references therein). In this paper we have focused on matter-energy subsystems, and it is already clear that the accreting binaries we have considered have *boundaries* (2), *ingestor* functions through accretion (3), *matter-energy storage* through reserves (7), and an *extruder* function (8) through ejecta and jets.

The *distributor* function (4) is less obvious because distribution around the components of an organism happens at a lower scale, but the stellivore interpretation would indeed expect mechanisms to distribute the energy on or near the surface of WDs, NSs and BHs.

The *converter* (5) function can be inferred indirectly, through remarking that energy is transformed between what is accreted, and what is ejected. For example in accreting WDs, the composition of nova ejecta displays unusual heavy-element abundance, and such heavy elements are not present in the accreted companion star (Prialnik 2001). The hypothesis that heavy elements are produced during the nova has to be ruled out, because the temperature is not high enough to produce heavier elements than helium. There remain two possibilities. Either the accreted matter is somehow mixed with WD material, or the accreted material is used as fuel to perform work and produces waste as heavy elements.

We have not discussed the *motor* function (9), but there are binaries that are moving fast in the galaxy (e.g. the extremely low-mass WD J0755 + 4906, the neutron star IGR J1104 - 6103 or the black hole XTE J1118 + 480). I have predicted (Vidal 2014, 260) that if stellivores are alive, the motion of such higher velocity binaries should not be random, but directed toward the nearest star, because it would be looking for the nearest next food source. We could also predict that higher velocity binaries have on average lower-mass companion, meaning that their energy source is almost exhausted, and they need to find and accrete a new star. Such energy-seeking behavior is already testable with existing data, and would constitute fairly intriguing evidence of intelligent behavior. There might even be room to model such a change of stellar companion in the NS system 4U 0513-40 that has an almost exhausted very low mass companion (0,05 solar masses, $M_\odot$). It has been argued that the unusual variation on two different time scales observed in this system (Maccarone et al. 2010) could be due to a third companion star (Prodan and Murray 2015). Could it be an energy switching configuration, a transition towards a new star to be accreted?

The *supporter* function (10) maintains the proper spatial relationships between the components. One could argue that the orbital and magnetospheric parameters contribute to this support function if they are indeed fine-tuned to ensure the living functions, and if they keep adapting for efficient controlled accretion and ejection.

What is cruelly missing in this picture are the information subsystems (third column). The notable exception is the *timing* (20) subsystem, with the Pulsar Positioning System that exists in our galaxy thanks to MSPs accelerated through accretion, a galactic navigation system intriguingly and amazingly accurate down to 100 meters. I have made a detailed analysis on how to test whether MSPs might have been engineered (Vidal 2019), and argued that even if the pulsar positioning system is natural, it remains extremely useful for setting galactic timing, navigation and metadata communication standards (Vidal 2017).

It is also worth noting that traditional SETI looks only at information signals in the environment, the *output transducer* (19) and has found none so far. By contrast, by broadening the search to all 20 living subsystems, the stellivore interpretation shows that up to 10 living subsystems behavior are consistent or have already been observed with accreting binaries.

2 Energy rate densities of binaries

Let us now compute the ERD of 130 WDs, 30 NSs, and 19 BHs. For this we need to simply use the accretion rate (noted $\dot{M}$), which is a measure of energy flow (expressed in solar mass per year, $M_\odot.y^{-1}$), and divide it by the mass of the primary WD, NS or BH

(in solar mass, $M_\odot$). In astrophysics and astronomy there are often many uncertainties regarding the calculation of accretion flows, which is model dependent. The mass determination of the compact star is also subject to varying uncertainties, depending on various observational constraints such as its distance, inclination, etc.

To compute the ERD, we also have the issue of determining how much of the accreted matter is converted into energy. 100% efficiency would mean perfect matter to energy conversion. On a first approximation, we can use the well known property that efficiency of energy conversion simply depends upon how compact the star is, via the formula:

$$\eta = \frac{GM}{c^2 R}$$

where G is the gravitational constant, c the speed of light, M and R the mass and radius of the compact star. Given that WDs in our data selection weight on average 0,78 $M_\odot$, assuming a 5000km radius, this leads to an efficiency $\eta = 2{,}3 \times 10^{-4}$. This results to an average ERD of $4{,}74 \times 10^{4}$ $erg.s^{-1}.g^{-1}$ (see table 2). One could also argue that accretion unto WDs is not the primary source of energy and that one should take instead nuclear burning as the main source of energy (Frank, King, and Raine 2002, 2). In that case, nuclear fusion has an efficiency of $\eta = 0{,}007$ and the ERD in our sample becomes much higher, $1{,}44 \times 10^{6}$ $erg.s^{-1}.g^{-1}$.

Name	**Mass (solarmass)**	**Accretion rate $\dot{M}$ (solarmass.y^{-1})**	**ERD (erg.s^{-1}.g^{-1})**
2325+8205	0,75	1,66582E-09	1,45E+04
AB Dra	0,8	1,74514E-09	1,43E+04
AH Her	0,95	2,69704E-09	1,86E+04
AM Cas	0,55	1,50717E-09	1,79E+04
AQ Eri	0,65	2,22109E-10	2,24E+03
AR And	0,75	1,58649E-09	1,38E+04
AT Ara	0,53	2,53839E-08	3,13E+05
AT Cnc	0,75	3,17299E-09	2,77E+04
AY Lyr	0,75	6,34597E-10	5,54E+03
BD Pav	1,15	1,11054E-10	6,32E+02
BF Ara	0,67	1,18987E-09	1,16E+04
BF Eri	1,28	2,53839E-10	1,30E+03
BI Ori	0,75	7,93246E-10	6,92E+03
BV Cen	1,24	2,14177E-09	1,13E+04
BV Pup	0,75	2,77636E-09	2,42E+04
BX Pup	0,75	1,42784E-09	1,25E+04
BZ UMa	0,76	5,71137E-11	4,92E+02
CH UMa	1,26	1,58649E-10	8,24E+02
CN Ori	0,74	1,58649E-08	1,40E+05
CW Mon	0,75	6,34597E-10	5,54E+03
CY Lyr	0,75	2,69704E-09	2,35E+04
CY UMa	0,69	1,66582E-10	1,58E+03
CZ Ori	0,55	3,64893E-09	4,34E+04
DI UMa	0,75	3,49028E-10	3,04E+03
DO Dra	0,83	3,33163E-11	2,63E+02
DX And	0,75	2,06244E-09	1,80E+04
EI Psc	0,65	7,93246E-12	7,98E+01
EM Cyg	1	1,66582E-08	1,09E+05
ER UMa	0,73	1,42784E-09	1,28E+04
ES Dra	0,58	7,93246E-10	8,95E+03
EY Cyg	1,1	2,61771E-10	1,56E+03
EZ Lyn	0,75	3,96623E-12	3,46E+01
FH Lyn	0,75	1,74514E-10	1,52E+03
FO And	0,75	5,23543E-10	4,57E+03
FO Aql	0,55	6,34597E-10	7,55E+03
FO Per	0,4	5,71137E-09	9,34E+04
FS Aur	0,55	3,49028E-10	4,15E+03
FT Cam	0,75	1,98312E-12	1,73E+01
GD 552	0,77	1,11054E-12	9,43E+00
GY Cnc	0,99	2,06244E-10	1,36E+03
HL CMa	0,83	2,77636E-09	2,19E+04
HM Leo	0,75	4,5215E-11	3,94E+02
HS Vir	0,68	4,60083E-11	4,43E+02
HW Boo	0,75	1,82447E-11	1,59E+02
HX Peg	0,75	2,37974E-09	2,08E+04
IR Gem	0,69	1,18987E-10	1,13E+03
IX Dra	1,4	1,74514E-10	8,15E+02
KS UMa	0,94	3,56961E-11	2,48E+02
KT Per	0,75	1,50717E-09	1,31E+04
KV Dra	0,71	4,75948E-11	4,39E+02
LL Lyr	0,75	1,42784E-09	1,25E+04
LX And	0,75	1,34852E-09	1,18E+04
NY Ser	0,81	5,31475E-10	4,29E+03
OU Vir	0,7	2,22109E-10	2,08E+03
PU CMa	0,46	3,88691E-11	5,53E+02
PY Per	0,75	1,98312E-10	1,73E+03
QW Ser	0,85	4,20421E-10	3,24E+03
QZ Ser	0,75	9,51896E-11	8,30E+02
QZ Vir	0,71	8,72571E-10	8,04E+03
RU LMi	0,75	3,17299E-10	2,77E+03
RU Peg	1,06	1,90379E-09	1,17E+04
RX And	1,14	1,03122E-09	5,92E+03
RY Ser	0,75	7,93246E-10	6,92E+03
RZ LMi	1	3,25231E-10	2,13E+03
SS Aur	1,08	7,93246E-10	4,80E+03
SS Cyg	0,81	3,49028E-09	2,82E+04
SS UMi	0,66	1,90379E-10	1,89E+03
ST Cha	0,75	1,11054E-08	9,69E+04
SU UMa	0,68	4,5215E-10	4,35E+03
SV CMi	0,75	1,18987E-09	1,04E+04
SW UMa	0,71	1,42784E-10	1,32E+03
SX LMi	0,67	5,07678E-11	4,96E+02
SY Cnc	0,75	2,37974E-08	2,08E+05
TT Crt	1	3,25231E-10	2,13E+03
TW Tri	0,75	1,82447E-09	1,59E+04
TW Vir	0,91	5,55272E-10	3,99E+03
TY PsA	0,87	2,37974E-10	1,79E+03
TY Psc	0,7	6,34597E-10	5,93E+03
TZ Per	0,75	1,18987E-08	1,04E+05
U Gem	1,17	7,13922E-10	3,99E+03
UY Pup	0,75	1,82447E-09	1,59E+04
V1159 Ori	0,72	1,34852E-09	1,23E+04
V1316 Cyg	0,72	4,12488E-09	3,75E+04
V1454 Cyg	0,75	8,72571E-13	7,61E+00
V1504 Cyg	0,67	1,34852E-10	1,32E+03
V342 Cam	0,75	1,90379E-11	1,66E+02
V355 UMa	0,75	8,72571E-11	7,61E+02

V392 Hya	0,75	2,06244E-09	1,80E+04
V426 Oph	0,9	8,72571E-10	6,34E+03
V478 Her	0,75	3,17299E-09	2,77E+04
V503 Cyg	0,73	5,31475E-10	4,76E+03
V513 Peg	0,75	3,64893E-10	3,18E+03
V516 Cyg	0,75	7,93246E-09	6,92E+04
V521 Peg	0,75	5,55272E-11	4,84E+02
V537 Peg	0,75	1,66582E-09	1,45E+04
V630 Cas	1,01	1,18987E-07	7,71E+05
V713 Cep	0,75	2,06244E-12	1,80E+01
V729 Sgr	0,75	3,25231E-10	2,84E+03
V792 Cyg	0,75	4,04556E-09	3,53E+04
V811 Cyg	0,75	3,33163E-10	2,91E+03
V844 Her	0,46	1,66582E-10	2,37E+03
V893 Sco	0,89	1,18987E-10	8,75E+02
VW Hyi	0,67	4,91813E-10	4,80E+03
VW Vul	0,35	3,09366E-09	5,78E+04
VZ Pyx	0,8	2,37974E-10	1,95E+03
WW Cet	0,83	6,34597E-10	5,00E+03
WX Hyi	0,9	2,93501E-10	2,13E+03
X Leo	1,03	8,72571E-10	5,54E+03
YZ Cnc	0,82	7,13922E-10	5,70E+03
Z Cam	0,99	3,80758E-09	2,52E+04

AE Aqr	0,63	1,74514E-09	1,81E+04
BG CMi	0,8	3,17299E-09	2,59E+04
BK Lyn	0,41	1,03122E-09	1,65E+04
FO Aqr	0,75	1,34852E-08	1,18E+05
IX Vel	0,82	5,55272E-09	4,43E+04
LQ Peg	0,75	2,30041E-08	2,01E+05
MV Lyr	0,73	7,13922E-09	6,40E+04
RR Pic	0,95	1,58649E-07	1,09E+06
RW Sex	0,9	1,11054E-08	8,07E+04
RW Tri	0,55	1,58649E-08	1,89E+05
TT Ari	0,9	1,11054E-08	8,07E+04
TV Col	0,75	1,18987E-08	1,04E+05
TX Col	0,54	1,90379E-08	2,31E+05
UX UMa	0,9	6,34597E-09	4,61E+04
V1084 Her	0,75	6,34597E-09	5,54E+04
V1223 Sgr	0,93	8,72571E-09	6,14E+04
V3885 Sgr	0,7	1,66582E-08	1,56E+05
V592 Cas	0,81	1,50717E-08	1,22E+05
V603 Aql	1,2	3,80758E-09	2,08E+04
V795 Her	0,69	7,29787E-08	6,92E+05
AVERAGE	**0,78584**	**5,72972E-09**	**4,74E+04**

Table 2 - Energy rate density of 130 white dwarfs in accretion. Starting from AE Aqr and downwards are nova-like systems, while above are cataclysmic variable systems. I have not taken into account the error bars in the mass and accretion rate ($\dot{M}$) estimates, as my goal is to have an ERD order of magnitude estimate. We assumed $\eta = 2{,}3 \times 10^{-4}$. Data from (Dubus, Otulakowska-Hypka, and Lasota 2018).

Name	**Mass (solarmass, assumed)**	**Accretion rate $\dot{M}$ (solarmass.y^{-1})**	**ERD (erg.s^{-1}.g^{-1})**
4U 0513-40	1,4	2,379E-10	4,83E+05
EXO 0748-676	1,4	1,00003E-10	2,03E+05
4U 0919-54	1,4	4,3225E-11	8,78E+04
4U 1608-52	1,4	2,38194E-10	4,84E+05
4U 1636-536	1,4	4,9205E-10	1,00E+06
MXB 1659-298	1,4	5,0024E-10	1,02E+06
4U 1702-429	1,4	2,60691E-10	5,30E+05
4U 1705-44	1,4	5,64698E-10	1,15E+06
XTE J1710-28	1,4	1,05661E-10	2,15E+05
4U 1724-307	1,4	3,51E-10	7,13E+05
4U 1728-34	1,4	5,55157E-10	1,13E+06
KS 1731-260	1,4	6,88037E-10	1,40E+06
4U 1735-44	1,4	1,42882E-09	2,90E+06
SAX J1747,0-	1,4	5,915E-10	1,20E+06
GX 3+1	1,4	1,846E-09	3,75E+06
SAX J1748,9-	1,4	1,40156E-09	2,85E+06
EXO 1745-248	1,4	7,01527E-10	1,43E+06
4U 1746-37	1,4	2,03927E-09	4,14E+06
SAX J1750,8-	1,4	5,44375E-10	1,11E+06
GRS 1747-312	1,4	3,23143E-10	6,56E+05
SAX J1808,4-	1,4	1,43E-10	2,91E+05
GX 17+2	1,4	1,53183E-08	3,11E+07
3A 1820-303	1,4	7,9768E-10	1,62E+06
XB 1832-330	1,4	1,105E-10	2,24E+05
Ser X-1	1,4	3,08286E-09	6,26E+06
HETE J1900,1	1,4	9,425E-11	1,91E+05
Aql X-1	1,4	3,58389E-10	7,28E+05
4U 1916-053	1,4	1,89614E-10	3,85E+05
4U 2129+12	1,4	9,62E-11	1,95E+05
Cyg X-2	1,4	1,40731E-08	2,86E+07
AVERAGE	**1,4**	**1,5759E-09**	**3,20E+06**

Table 3 - Energy rate density of 30 neutron stars in accretion. To obtain accretion rates ($\dot{M}$), we used the soft color prior to burst (Normalize F_{per}) multiplied by $1{,}3 \times 10^{-8}$ to obtain values in solar masses per year, from column 15 in table 6 of (Galloway et al. 2008). We assumed $\eta = 0{,}1$.

Name	Mass (solarmass)	Accretion rate $\dot{M}$ (solarmass.y^{-1})	ERD (erg.s^{-1}.g^{-1})
GRO J0422+32	3,97	2,67E-11	1,91E+04
A620-00	11,00	5,43E-11	1,40E+04
GRS 1009-45	3,90	2,63E-10	1,92E+05
XTE J1118+480	8,53	2,00E-10	6,67E+04
GS 1124684	7,50	3,33E-10	1,26E+05
GS 135464	5,75	1,63E-09	8,08E+05
4U 154347	9,40	1,13E-09	3,41E+05
XTE J1550564	10,50	1,59E-09	4,30E+05
XTE J1650500	2,73	1,09E-10	1,14E+05
GRO J165540	6,30	8,73E-10	3,94E+05
MAXI J1659352	5,80	1,41E-10	6,92E+04
GX 3394	5,30	1,27E-08	6,81E+06
4U 1705250	4,73	2,92E-10	1,76E+05
GRS 1915+105	14,00	1,55E-07	3,16E+07
GS 2000+25	9,60	6,54E-11	1,94E+04
V404 Cyg	12,00	9,36E-10	2,22E+05
Cyg X-1	14,80	1,41E-08	2,71E+06
LMC X-1	10,91	6,58E-08	1,72E+07
LMC X-3	11,10	6,65E-08	1,70E+07
AVERAGE	**8,31**	**1,70E-08**	**4,12E+06**

Table 4 - Energy rate density of 19 transient black holes. We have not included the uncertainties about BH masses, but they are significant. When appropriate, we have taken averages in the plausible mass range. We assumed η = 0,1, and the data is from (Coriat, Fender, and Dubus 2012).

Turning to NSs and BHs, it is generally assumed that η = 0,1. Assuming an average typical NS mass of 1,4 $M_\odot$, we have an average ERD of 3,2 x 10^6 erg.s^{-1}.g^{-1} (see table 3). In the case of BHs, the data is less complete (there are fewer known systems, and higher uncertainties regarding their masses), but it gives an ERD of 4,12 x 10^6 erg.s^{-1}.g^{-1}(see table 4). One could argue that the 0,1 efficiency value is not realistic, as it is an estimation for non-rotating BHs. If a BH rotates up to its maximum speed, the efficiency could reach 0,4 (Thorne 1974). Such efficiency would lead to an average ERD of 1,65 x 10^7 erg.s^{-1}.g^{-1}.

The calculations presented here may be refined and thus represent only orders of magnitudes. Yet they all show extremely high ERDs. One can already see a hierarchy of ERD, which is higher for more compact accreting objects. In the stellivore interpretation, following the Barrow scale of civilizational development, the most compact would be the most advanced too (see e.g. Barrow 1998; Smart 2012; Vidal 2014, sec. 9.2.2; Vidal 2016). This seems to be consistent with ERD as a complexity metric, where higher ERD means more complex.

3 Discussion

One might argue that the high ERD values found in binaries are nothing special, and that one can also find high ERD in other accreting systems. As a control, I computed the ERD for 16 supermassive black holes (SMBHs), assuming an efficiency η = 0,1, I found an ERD of 8,4 x 10^6 erg.s^{-1}.g^{-1} (see Table 5).

Name	Mass (solarmass)	Accretion rate $\dot{M}$ (solarmass.y^{-1})	ERD (erg.s^{-1}.g^{-1})
3C 120	5,50E+07	3,67E-01	1,90E+07
NGC 3516	4,27E+07	6,00E-03	4,00E+05
NGC 3783	2,95E+07	2,30E-02	2,22E+06
NGC 4051	1,91E+06	1,00E-03	1,49E+06
NGC 4151	1,32E+07	2,00E-03	4,32E+05
Mrk 766	3,47E+06	2,10E-02	1,72E+07
MCG-6-30-15	1,55E+06	1,20E-02	2,20E+07
Mrk 590	4,79E+07	1,10E-02	6,54E+05
Mrk 110	2,51E+07	2,38E-01	2,69E+07
NGC 4395	3,63E+05	4,00E-05	3,13E+05
NGC 5506	8,71E+07	1,70E-02	5,55E+05
NGC 5548	6,76E+07	3,50E-02	1,47E+06
Mrk 509	1,45E+08	3,01E-01	5,92E+06
Ark 564	7,94E+06	2,80E-02	1,00E+07
NGC 7469	1,23E+07	9,90E-02	2,29E+07
Ark 120	1,86E+08	1,80E-01	2,75E+06
Average	**4,54E+07**	**8,38E-02**	**8,40E+06**

Table 5 - Energy rate density of 16 supermassive black holes (SMBHs) in Seyfert 1 galaxies, data from (Meyer-Hofmeister and Meyer 2011 and references therein).

This is indeed extremely high. However, one could argue that an efficiency of $\eta = 0{,}1$ is not realistic, and some models propose values as low as $\eta = 0{,}001$ (Armijo and Pacheco 2011). In that case, the average ERD is two orders of magnitude less, i.e. 8,4 x 10^4 erg.s^{-1}.g^{-1}. One could also nuance this result by remarking that Chaisson did not separate SMBHs from the rest of the stars in a given galaxy, and as such ends up with much lower ERD values for galaxies, about 0,5 erg.s^{-1}.g^{-1}. This unveils a general issue when computing ERDs, namely how to define the boundary of the system we are considering. In the case of stellivores, I interpret only the primary WD, NS, or BH as living, and the secondary star just as its energy source. So it makes sense not to normalize by the mass of both stars.

One may also object that some trivial systems can have high ERDs. Chaisson (2001, 144) discusses candles that indeed have an ERD of about 10^6, and other high energy flows situations. However, there is no energy control from the candle itself (it doesn't switch itself on and off), and the system rapidly reaches equilibrium after the wax is consumed. Candles obviously also lack other living systems features (see also Vidal 2014, sec. 9.5.9).

Next to the candle objection, a more sophisticated counter-example that involve a feedback loop is the *geyser objection*. I have not computed the ERD of geysers yet, but let's look at their dynamics instead. Deacon (2012, 118) describes the eruptions of the famous Old Faithful geyser at Yellowstone park in the following way:

> "It erupts on a highly regular basis because of the way that the temperature and pressure of the subsurface water is self-regulated around a mean value by the interplay of geothermal heating, the pressure of steam, and the weight of the column of water in the underground vent. As the water is heated to the point of boiling, the pressure of the released steam reaches a value sufficient to drive the overlaying column of water upward; but in so doing it "resets" the whole system, allowing new water to accumulate, boil, and reach this same threshold, again and again. So the water temperature and stem pressure oscillates around a constant value and the geyser erupts at regular intervals".

Are accreting binaries not more sophisticated than the dynamics of a geyser? Superficial astrophysical models of accreting binary stars indeed resemble the modeling of a geyser. One can point two fundamental differences however. First, there is no energy

transformation, second the eruptions of accreting binaries are not as predictable as geysers.

The geyser system does show *one single* natural feedback cycle. However, living systems have many feedback cycles, mediated by control mechanisms. If the stellivore hypothesis is true, we expect more than one simple and trivial feedback cycle, and also control mechanisms. In a way, we already did hint at control systems when discussing the various energy flow controls. Considering the information subsystems, there is also no set of geysers that can provide the equivalent of a GPS… High energy interactions lead to destructive explosions if they are unchecked. For example, combining air and fuel leads to an explosion. However, if both are carefully put in a well-designed cylinder, they can form an internal combustion engine, a controlled explosion that is most useful for our civilization. The same reasoning may apply with accretion and nuclear reactions. Unchecked nuclear reactions can and have lead to catastrophes on Earth. In the universe, accretion or nuclear reactions can also rapidly lead to supernovae or other cosmic explosions. However, in the accreting binaries we have discussed, the energy is channeled via gravity, magnetic fields and further nuclear reactions occur, sometimes slowly - actually, all the forces of nature seem to be involved.

4 Conclusion

We have proposed a new technosignature for astrobiology and SETI: to simply follow the energy rate density. We computed ERD of many binary star systems in accretion, which is also new, and reveal that their ERD is very high. We have also reviewed many living clues regarding accreting binaries, such as their variety, their existence far from thermodynamic equilibrium, the need to fine-tune models to explain them, the apparent existence of energy reserves, accretion control and ejection control.

The two possible conclusions from this paper are somehow embarrassing. First, if the stellivore hypothesis is wrong, then the extremely high ERDs found would mean that ERD is not a proper and reliable complexity metric, and that big history needs more solid foundations. This might be mitigated with new informational or computational metrics to consider in addition to or instead of ERD (see e.g. Delahaye and Vidal 2018). Second, if the stellivore hypothesis is true, then complexity would have risen dramatically at other places in the galaxy, and the story of rising complexity would not be centered locally on planet Earth anymore, but would be much bigger, richer, and fascinating.

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