ASTROPHYSICAL ACCRETION: THE APPROACH TO THE IRRATIONALITY HORIZON

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Abstract. Accretion, broadly defined, is the acquisition of relatively small amounts of stuff by an object that has already acquired its identity. It is exceedingly widespread in astrophysical systems from comets to the cosmos. We provide an overview of contexts in which accretion occurs and is of importance, noting, when possible, the first discussion of the process in each context.

INTRODUCTION: THE PROPER INTERFACE BETWEEN THEORY AND OBSERVATION

The subtitle of this historical overview derives from a drawing, shown by Richard McCray during a 1977 conference on Active Galactic Nuclei in Cambridge (McCray 1978) and reproduced as the frontispiece of the proceedings of an earlier conference in the present series (Holt et al. 1992), in which some theorists bravely resist the attractions of a new idea and others quickly fall within the Schwarzschild or irrationality horizon, some colliding on the way and generating additional heat. A closely related art form consists of Feynman graphs of world lines of theorists interacting with data. The normal, or Kirchhof's Law, theorist encounters a datum, shortly thereafter generates one theory, and goes on his way, leaving the theory to fend for itself in later encounters with new data. The self-excited theorist generates a series of theories even in the absence of data and is himself knocked into a random walk by the effort. The super-radiant theorist, impacted by a single surprising datum, generates a whole extended air shower of theories and is totally consumed thereby, while the super-luminal theorist manages to send a seemingly spontaneous theory backward in time to encounter an incoming observation before it can hit him. The rare, truly successful examples of this are dignified by the name prediction, though the word is sometimes also applied to the first category, which are really explanations.

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Those who have taught large, introductory courses in astronomy or physics know that you can improve the grade on the final exam by telling the students what the questions will be ahead of time – but not by much. In this spirit, we offer the following list, whose answers will indeed appear in the pages that follow. Who (or who first)

1. Said "it is easier to believe that two Yankee professors would lie than that stones would fall from the sky?"
2. Investigated accretion-induced explosions?
3. Suggested accretion-induced collapse of white dwarfs near the Chandrasekhar limit?
4. Pointed out that material accreted from a companion would go into a ring or disk?
5. Provided observational evidence for such a disk in an active binary?
6. Wrote a Ph.D. thesis about evolution of close binaries with mass transfer?
7. Calculated Bondi-Hoyle-Lyttleton accretion and got it wrong?
8. Said Sco X-1 is a binary with accretion onto a neutron star?
9. Discovered something in 1492?

A NEARLY EXHAUSTIVE LIST

What follows is an outline of all the contexts I have been able to think of where accretion is important (if it truly happens) and some related issues. Additions would be very welcome.

By the Earth

- Manna (suggested by Eli Dwek)
- meteorites (a victim of the Enlightenment)
- comets (as a source of volatiles and organic material)
- asteroids and extinctions (enough already written)
- formation of the Moon as a Big Splash

Elsewhere in the Solar System

- impact cratering of Moon, Mercury and all (acceptance slow)
- volatile sources on other planets

By the Sun

- replacement of mass lost in radiation (Eddington)
- primary energy source
- heating of corona
- sun-grazing comets

- solar wind vs. Poynting-Robertson effect
- proposed solutions to solar neutrino problem (inhomogeneous sun; central black hole; old core + recent additions)

Single Stars

- alternative to star formation (see Trimble 1997)
- primary energy source (early 19th century)
- Beta Pic and other stars with disks and/or star-grazing comets
- Lambda Bootes stars
- white dwarfs (hydrogen and/or metals from ISM)
- single neutron stars (faint X-ray sources; galactic background)

Star Formation

- what stops the accretion?
- source of pre-main-sequence activity (T Tauri stars, Herbig Ae/Be stars, FUORs, etc.)

Binary Stars

- resolving the Algol paradox
- Ba II stars, CH subgiants
- blue stragglers
- cataclysmic variables
- accretion-induced collapse of white dwarfs to make neutron stars (extra quiz question: why not AIC of neutron stars to make Cyg X-1 etc.?)
- accretion-induced explosions of WDs as Type Ia supernovae
- X-ray binaries

Normal Galaxies

- high velocity clouds
- satellite galaxies
- fueling of central star formation
- bars and spiral arms

Active Galaxies

- feeding of monsters
- increasing black hole masses to turn off monsters

The Universe

- growth of mass inside the horizon (much less than a single galaxy at thetime of Big Bang nucleosynthesis)

Accretion vs. Excretion (or Explosions/Outflow

- solar corona

- period changes in close binaries
- spiral arms
- star clusters and AGNs (the legacy of V.A. Ambartsumian)
- AE Aqr

IN AND AROUND THE SOLAR SYSTEM

Meteorites

This is not expert information and has been culled from random library books and encyclopedias. Many pre-modern cultures seem to have been aware that stones and chunks of metal occasionally fall from the sky and to have regarded specific examples as of religious or magical significance (and it is presumably this viewpoint that later led to early-modern scientists rejecting the whole idea). An important case is Al-Hajaru 'l-Aswad, the Black Stone in the Ka'aba. In place long before the advent of Mohammed, the Messenger of God, upon whom peace, it is generally regarded by both Moslem and non-Moslem authorities as a stony meteorite of very dark color (possibly to be rendered white when the world is saved). The Prophet apparently never endorsed this view, but allowed the shrine to remain and to remain important.

Other widely-mentioned ancient examples include the "stones from heaven" in the book of Joshua, the base of the statue of Artemus at Ephesus (very strangely described in standard translations of Acts of the Apostles), Chinese examples collected during the Eastern Chou Dynasty (about 687 and 644 BCE), the Shield of Numa Popilius at Rome, and objects in temple of Venus at Cyprus, Aegospotami (wherever that is!), and elsewhere.

The oldest western-style records of a fall actually seen pertain to that in Ensisham, Alsace on 16 November 1492. It weighs about 260 lb. Not long afterward scientists of the Enlightenment, especially members of the French Academy and the Royal Society, declared that stones do not fall from the sky, and it was all primitive superstition.

Restoration of the proper, unEnlightened view took some time. The process began with the Pallas iron meteorite found in Siberia (by Pallas) in 1749. A 1794 book about it by Chladni (of the zones on vibrating plates) made a case that the mineral composition could not be native to Earth and suggested spent fireballs and pieces of a broken-up planet as the source.

A fall at Wold Cottage, Yorkshire on 13 December 1795 and examination by suitably eminant people rendered meteorites respectable in England. The L'Aigle fall on 26 April 1803, investigated by Laplace and Biot, performed the same service for France. The US was a little behind in those days, and it was a report of the Weston, Connecticutt fall on 17 December 1807 by Profs. Silliman and Kingsley of Yale that prompted Thomas Jefferson's remarks about Yankee professors.

Earth and Moon

At one time, all craters were supposed to be volcanic (since that is the sort you can usually see in formation). The "discovery" that at least the Berringer crater in Arizona resulted from an impact was made repeatedly from the 1920's onward for several decades, with increasing numbers of converts each time. Much the same happened for lunar cratering somewhat later and, while Ralph Baldwin's book, The Face of the Moon (Baldwin 1949) was a turning point for many of its readers, other early converts to impact cratering whose names are rightly associated with acceptance of the process as important in the history of many solar system objects were Robert Dietz, Fred Whipple, Peter Millman, and Eugent Shoemaker (Baldwin 1995).

An on-going discussion in the geophysical community concerns the balance between outgassing and cometary (etc.) impacts as the sources of volatiles (air and water) on the Earth and other terrestrial planets. An important diagnostic is the ratio of deuterium to hydrogen. D/H in comets Hyakutake and Hale-Bopp is about twice that in the Earth's oceans (Owen et al. 1997), meaning that such comets cannot have been the dominant soure of terrestrial water (it is easy to increase D/H by evaporation, impossible to decrease it). And the less said about little comets the better.

Accreted material could also have contributed to the Earth's supply of organic material (Chyba and Sagan 1997 are the last to have mentioned this and so get credit in accordance with a well-known effect). Evidence in support is recent detection of slight excesses of the L-enantiomer of amino acids in the Murchison meteorite in contexts that rule out terrestrial contamination as the source (Cronin and Pizzavello 1997; Engel and Macko 1997).

The formation of the moon itself appears to have been in a sense accretory, with contributions from material splashed off the Earth and from the splasher, something about twice the mass of Mars in the most recent iteration (Ides et al. 1997; Cameron 1997; Lissauer 1997).

The Sun

That the solar corona must be hot became clear when Edlén (1942) identified a previously mysterious emission line as Fe XIV. Owing to the good offices of Pol Swings, the indentification was quickly publicized outside of Germany, and Vand (1943) came forth with the first accretion-based explanation, invoking the infall of solid particles like those responsible for Zodiacal light. Modern calculations suggest that these particles will actually fall out rather than in (owing to Poynting-Robertson acceleration) even if they were not carried by the solar wind. The next attempt was heating by the accretion of interstellar gas, put forward by Bondi, Hoyle, and Lyttleton (1947), and it is in this context that they did the first calculations of what we now call Bondi (etc.) accretion, pointing out that an earlier treatment by Eddington (1926) was inappropriate.

At least three proposed solutions of the solar neutrino problem have invoked some sort of accretion. The least outrageous is that the Sun might be chemically inhomogeneous, with 1.7% heavy elements only in its convective envelope and much lower metallicity further in, as a result of many bombarding comets. The lower central opacity would lower the core temperature and so reduce the flux of B^8 and Be^7 neutrinos. I associate the idea with the names of Beatrice Tinsley and A.G.W. Cameron, but have been unable to locate the reference.

Second was the idea that the Sun might be powered by accretion onto a small central black hole (Hawking 1971) and not by nuclear reactions at all. This is a classic example of those who do not read history being doomed to repeat it. Back in ante-Betheian times, Gamow (1937) and Landau (1938) had tried to run the Sun and other stars by accretion onto central small neutronized cores. Gamow and Teller (1939) quickly showed it would not work, though they credited the discredited idea only to Landau, not to Gamow!

Third, and from the leftest of fields, is the idea that the Sun consists of half a solar mass in a structure older than the Hubble time (and associated with some form of steady state universe) that has only recently added its outer half by accretion from interstellar gas (Hoyle 1975).

SINGLE STARS

That star formation is an accretion process is fairly obvious at least in light of last year's October conference (Holt and Mundy 1997). For some stars, the process continues long after. The classic example is Beta Pictoris and, at last count, there were 15 papers in the series showing that some of the accretion is in the form of comets. Other stars carrying on in more or less the same way have also proliferated, and we note only two of the most recent, HD 100546 (Grady et al. 1997) and Z And (Cheng et al. 1997).

The Sun and many other stars guard themselves from interstellar accretion with outgoing winds. Some white dwarfs must do the same, or, as Greenstein (1969) was first to note, the hydrogen-free atmospheres of the DB stars could not exist, even if the proper accretion rate were the relatively low one suggested by Eddington (1926). The situation has become more confused of late, because some of the hydrogen-depleted WD atmospheres do contain heavy elements, which must be recent arrivals from the ISM (Ruiz et al. 1997). Some DA white dwarfs also sport accreted metals (Holberg et al. 1997). Such accretion could also be to blame for the temperature inversion in the atmosphere of GD 156, which is unique among DAs in displaying its hydrogen lines in emission (Ferrario et al. 1997).

Accretion on single neutron stars must surely also occur once they stop throwing off pulsar winds. Individual faint sources of this type seem to be fairly rare (Manning et al. 1996; Blaes et al. 1995), which implies that they do not collectively contribute much of the galactic X-ray background. That they might was first suggested by Ostriker et al. (1970).

Segregation of metals in dust can, of course, produce composition anomalies whether the grains are coming or going, and we end this section with the edifying remark that Beta Pic is not a Lambda Boo star (Holwegar et al. 1997).

BINARY STARS, TYPES UP TO X

It is in the realm of close binaries that stellar accretion truly comes into its own. The topics are ordered more by the history of the stars' lives than by years in the 20th century, though there is some similarity in the two sequences, because little progress could be made until it was firmly established that stars expand as they use up their core hydrogen fuel. There were hints of this truth in pre-war work by Opik and by Hoyle and Lyttleton, but the details belong to the post-war period, with primary credit to Martin Schwarzschild.

If you want to know a very great deal about Roche lobes, you look in books by Zdenek Kopal, but the significance was first pointed out by Kuiper (1941), who also noted that the material should form a ring around the recipient and that binary orbit periods would be changed thereby. Kuiper was contemplating Beta Lyrae, which to this day remains one of the more extreme examples of anything you might want to contemplate in this field.

Blue stragglers are officially credited to Sandage (1953), though a couple of stars off the ends of main sequences appear in earlier HR diagrams. In any case, the idea that the responsible mechanism is mass transfer in a close binary belongs to McCrea (1964).

The Algol paradox comes under the heading of things that could not be paradoxical until the structure of giants was understood. The point is that in Algol and many other similar eclipsing binaries, the more evolved star is the less massive. The problem was codified by Struve (1953) who also provided hints about its solution to Crawford (1955), the first person to ascribe the apparent inversion to mass transfer. The first Ph.D. dissertation on the subject was that of Morton (1960) who demonstrated that the initial mass ratio would be reversed very quickly, on something like the thermal time scale of the mass-losing star. Morton was a student of Schwarzschild, who otherwise never seems to have taken much interest in accretion phenomena or the evolution of close binaries. Three groups quickly carried the mass transfer ball forward, though Morton was not a part of any of them, and the subject was ripe for review a decade later (Paczynski 1971), though the first person who tried to model the accreting star accurately was driven to distraction and out of astronomy (Benson 1970).

The accretor cannot, however, help screaming out its plight to the spectroscopist in cases where the transferred material has already been polluted by nuclear reactions in the primary. Well-known cases include dwarf carbon stars (which Schwarzschild once playfully said he would die if they existed, Bond 1997), with the first one identified by Dahn (1987), CH sub-giants (Bond 1974), and the barium stars (McClure et al. 1980). The duplicity of these giants with strong BaII lines was presented as a serendiptous discovery, but the investigation was in fact not a random one according to later statements by the discoverers.

Transfer of material back to an evolved primary as the secondary begins to expand was put forward by Hoyle (1955) as the "dog eat dog" scenario. Soon after, Crawford and Kraft (1956) described the emission lines in AE Aqr, a nova-like variable, as being indeed the result of accretion in a disk. At the time, this was flying in the face of received wisdom (meaning what people like Joy and Merrill thought, Kraft 1997), though it is now, of course, the basis of all discussion of the cataclysmic variables (Warner 1996). Nova explosions frequently remove more material than was accreted to trigger them, so that the accreting white dwarf paradoxically shrinks in mass.

It is, however, possible to imagine the opposite case, where accretion adds to the mass of the white dwarf. Just who deserves credit for which ideas still needs some sorting out. Schatzman (1945) attempted to produce supernovae with interstellar hydrogen piling up on a white dwarf. In fact, such hydrogen will flash when only 10^{-4-5} $M_\odot$ has accumulated, and the result is a nova, not a supernova. The points that something at the center must detonate (etc.), that this can only be carbon and oxygen, and that only a close companion is likely to contribute enough stuff to make it happen apparently gathered together in the dark. The first paper to put it all clearly together is Wheeler and Hansen (1971), but Wheeler (1997) says he does not believe they originated the idea, and would like to know who did!

That accretion (also from the interstellar medium) could trigger collapse rather than an explosion and that this might also be relevant to Type I supernovae appears as a one-liner in Mestel (1952), but when asked if he could remember any background, he first denied having said it, and then, after looking back at the paper, concluded that the background, if any, had disappeared completely (Mestel 1997). Collapse of a white dwarf to a neutron star as a result of accretion from a companion gained prominence with the discovery of very large numbers of millisecond pulsars in globular clusters, but van den Heuvel (1981) is probably not the first mention of the idea.

THE SORTING OUT OF X-RAY BINARIES AND "EDDINGTON ACCRETION"

X-ray emission from accreting binary systems was actually predicted (Hayakawa and Matsuoko 1964) after it had been seen from Sco X-1 (Giacconi et al. 1962), but before it had been understood to be seen, though they had in mind colliding winds rather than deep potential wells. Following the optical identification, it was modeled first as an accreting white dwarf (Cameron 1966, but also as late as Woltjer 1970). Credit for the model with a neutron star accreting from a companion has been claimed by several theorists (most no longer alive to defend themselves), but the first printed version seems to be Novikov and Zeldovich (1966), and the most widely read and cited early version to be Shkolvskii (1967). The initial glitch was the presumption that each proton that landed would make one photon carrying most of its kinetic energy. Hence accretion on white dwarfs would yield X-rays, and accretion on neutron stars gamma rays. This was sorted out by Zeldovich and Shakura (1969), but with slow diffusion to the west.

Thus, when the pulsating sources first appeared, Blumenthal et al. (1972) once again invoked white dwarfs, while Pringle and Rees (1972) and Shakura and Sunyaev (1973) properly put neutron stars at the centers of their accretion disks, whose importance had been pointed out by Prendergast and Burbidge (1968).

Since some X-ray binaries feature accretion from a stellar wind rather than a disk, this is perhaps as good a place as any to look at the differing accretion rates found for such a process. Eddington (1926) was attempting to decide whether the Sun and stars could recoup even the mass they lost in radiation by accretion of interstellar material (whose very existence was at the time still debated). He focussed on dust grains, which would act as non-interacting particles, so that only material actually curved into the path of the star would be captured. In contrast, Hoyle and Lyttleton (1939) were thinking of gas, a collisional and dissipative substance, and so allowed for capture of everything slowed down in the wake of the star. This leads to the familiar $1/V^3$ expression, where V is the velocity of the gas past the star. Bondi (1953) extended the concept to a star at rest, where, roughly, relative velocity is replaced by sound speed. Thus Eddington was not precisely wrong, but his result looks funny to modern eyes.

NORMAL GALAXIES

Things one might think of a galaxy picking up include other smaller galaxies and stray gas. Holmberg (1940, 1941) seems to have been the first to look at the former. He represented each galaxy with 37 light bulbs, the local gravitational potential with a photometer, and considered loss of tidal energy in close passages, mergers, and the possible contributions to making spiral arms. Later work has included the Searle-Zinn (1978) scenario for galaxy formation as, in general, an assembly-line process (in contrast to the Eggen, Lynden-Bell, and Sandage 1962 single-event model); the classic work by Toomre and Toomre (1972) showing how close encounters can produce tidal tails, fuel central star formation, and do many other wondrous things (also to this day one of the best-written astronomy papers I've seen); and Tremaine's (1976) discussion of the decay of the orbit of the LMC around the Milky Way, which must surely have been considered earlier, perhaps by Chandrasekhar?

Galaxy formation must have begun with inflowing gas. Does the inflow continue? Oort (1966) suggested that the high-velocity clouds of hydrogen seen in 21 cm velocity maps are virgin material being accreted at a rate of about one solar mass per year. Such accretion has been incorporated into models of galactic chemical evolution as a possible solution for the G dwarf problem (the paucity of low-metallicity low mass stars in the solar neighborhood) by Fowler (1972), Quirk and Tinsley (1973), and many later invokers of adjustable parameters. Fowler said it best, "Here these stars are burning their hearts out trying to make heavies, and those bastards keep diluting it." If infall at this rate were a general property of spiral galaxies, they would radiate an average of 10^{41} erg/sec in diffuse X-rays, which is rather more than we see (Fabbiano 1989), and Oort's case should probably be regarded as "not proven". There were, at last count, at least 11 models for high velocity clouds (Wakker et al. 1996), many of which should fall before data now in preprint form.

ACTIVE GALAXIES AND THE UNIVERSE

Quintillas of AGN models have swum into and out of the literature since the optical identification of Cygnus A in 1953. Most (though not all) of the survivors have invoked some sort of accretion onto a central, massive black hole. The first two were Salpeter (1964) and Zeldovich and Novikov (1964), and the disk was added to Lynden-Bell (1969).

The mass of the observable universe (part within the horizon) increases monotonically with time in standard Friedmann-Robertson-Walker models. It is left as an exercise for the reader to calcalate the rate of accretion of the observable universe.

ACCRETION VS. EXCRETION

For a number of the objects and systems mentioned above, there have been competing models, one invoking accretion of matter, the other outflow or excretion. We can do a brief score sheet on which has won in each case.

The solar corona is clearly part of an outflow or solar wind, not accretion-heated. Virtually every class of close binary star has some members whose orbit periods are changing faster than you would expect from single-star evolution. Kuiper (1941) pointed out that mass exchange or loss could contribute. Which sign the effect has depends on whether the stuff that relocates has more or less than its fair share of angular momentum, and structural changes due to magnetic cycles of the component stars are now thought to be major contributor.

In a curious bit of irony, AE Aqr, the system for which Crawford and Kraft (1956) first proposed as an accretion disk, now seems to be excreting (Hollis et al. 1997; Kuipers et al. 1997).

Star formation, active galactic nuclei, and spiral arms have all been attributed to outflow of material from some mysterious reservoir, mostly by Ambartsumian (1947, 1960, and many other papers), although Sir James Jeans at one time suggested that spiral arms might represent material entering our universe from elsewhere. Ambartsumian's influence still lingers on these topics, at least in Armenia, where Mirzoyan and Akopian (1997) have just ascribed the formation of at least the low mass stars in OB associations to outflow from dense protostellar objects.

ANSWERS TO THE QUIZ AND PARTING SHOT

By now, you are in a position to fill in the blanks along the following lines:

1. Thomas Jefferson in 1807
2. Evry Schatzman in 1945
3. Leon Mestel in 1952
4. Gerard Kuiper in 1941
5. John Crawford and Robert Kraft in 1956
6. Don Morton in 1960
7. Arthur Eddington in 1926
8. Yakov Zeldovich and Igor Novikov in 1966
9. An anonymous Alsatian subject of King Maximilian I in 1492 (also, of course, Columbus, but he was not primarily an astronomer)

Roughly 20 years ago, Paczynski described bandwagons and the progress of astronomy in these terms: "In the 1950's everything was magnetic fields. In the 1960's, everything was black holes. Now [c. 1976], all of a sudden, everything is mass transfer in close binaries." And, looking over the program of the present conference, one is tempted to say that, in 1997, everything was advection-dominated accretion, which combines at least two of the three previous centers of irrationality horizons or even all three if you are inclined to give Howard Greyber the last word.

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