Accretion Phenomena and Related Outflows, IAU Colloquium 163
ASP Conference Series, Vol. 121, 1997
D.T. Wickramasinghe, L. Ferrario, and G.V. Bicknell, eds.

Hydrodynamic Simulations of Wind-Accretion with Gradients

M. Ruffert

Max-Planck-Institut für Astrophysik, Postfach 1523, D-85740 Garching, Germany

Abstract. I investigate the hydrodynamics of three-dimensional Bondi-Hoyle-Lyttleton accretion including velocity and density gradients in the incoming flow and determine how much angular momentum is accreted. A medium taken to be an ideal gas with an adiabatic index of 5/3 or 4/3 moves at supersonic speeds (Mach 3 and 10) past a totally absorbing sphere with a radius of 0.1 or 0.02 accretion radii. The velocity within the medium is given a gradient of 3% or 20% (over one accretion radius). I find that a substantial amount (0.1 to 0.7) of the specific angular momentum available within one accretion radius in the upstream flow actually is accreted. The amount is smaller for smaller accretor sizes. The flow is roughly just as unstable as in the previous models without gradients. The unstable flow is best seen in animated sequences.

1. Introduction

The Bondi-Hoyle-Lyttleton (BHL) model for accretion of matter from a homogeneous medium onto compact objects has been studied intensively since the first ideas were published (Hoyle & Lyttleton 1939, Bondi & Hoyle 1944). Usually, the accretion rates of various quantities, like mass, angular momentum, etc., including drag forces are of interest as well as the properties of the flow, (e.g. distribution of matter and velocity, stability, etc.). However, if the assumption of homogeneity of the surrounding medium is dropped, e.g. by assuming some constant gradient in the density or the velocity distribution, the consequences on the accretion flow remain very unclear, especially concerning the specific angular momentum of accreted matter. Two opposing points of view developed. On the one hand a large amount of anugular momentum might be accreted (Dodd & McCrea 1952; Illarionov & Sunyaev 1975; Shapiro & Lightman 1976; Wang 1981) from the accretion cylinder, while on the other hand, the BHL recipe might preclude large angular momenta (Davies & Pringle, 1980).

Using numerical simulations, I compare the accretion rates of several quantities (especially angular momentum) of accretion flows *with* gradients to the previous results of accretion *without* gradients (e.g. Ruffert 1994). In this first investigation I only simulate models with gradients of the velocity distribution (no gradient of the mass density).

The distribution of matter is discretised on multiply nested equidistant Cartesian grids (e.g. Berger & Colella, 1989) and is evolved using the "Piecewise Parabolic Method" (PPM) of Colella & Woodward (1984). The equation of state is that of a perfect gas with a specific heat ratio of $\gamma = 5/3$ or $\gamma = 4/3$. The model of the maximally accreting, vacuum sphere in a softened gravitational potential is summarized in Ruffert & Anzer (1995).

Table 1. Parameters and some computed quantities for all models. $\mathcal{M}_\infty$ is the Mach number of the unperturbed flow, ε_v the parameter specifying the strength of the gradient, γ the ratio of specific heats, $R_\star$ the radius of the accretor, g the number of grid nesting depth levels, δ the size of one zone on the finest grid, ϵ the softening parameter (zones) for the potential of the accretor (see Ruffert, 1994), t_f the total time of the run (units: R_A/c_∞), $\overline{\dot{M}}$ the integral average of the mass accretion rate, S one standard deviation around the mean $\overline{\dot{M}}$ of the mass accretion rate fluctuations, the number N of zones per grid dimension is 32, and the size of the largest grid is $L = 32R_\mathrm{A}$.

Model	$\mathcal{M}_\infty$	ε_v	γ	$R_\star$ (R_A)	g	δ (R_A)	ϵ	t_f	$\overline{\dot{M}} \pm S$ ($\dot{M}_\mathrm{BH}$)
IT	3	-0.03	5/3	0.02	10	1/512	8	4.82	0.72 ± 0.04
IS	3	-0.03	5/3	0.02	9	1/256	3	13.9	0.53 ± 0.09
IM	3	-0.03	5/3	0.10	7	1/64	4	26.6	0.79 ± 0.06
JS	10	-0.03	5/3	0.02	9	1/256	3	2.93	0.45 ± 0.09
JM	10	-0.03	5/3	0.10	7	1/64	4	10.3	0.72 ± 0.05
KS	3	-0.20	5/3	0.02	9	1/256	3	6.89	0.54 ± 0.09
KM	3	-0.20	5/3	0.10	7	1/64	4	20.3	0.95 ± 0.19
LS	10	-0.20	5/3	0.02	9	1/256	3	1.94	0.35 ± 0.08
LM	10	-0.20	5/3	0.10	7	1/64	4	8.54	0.72 ± 0.17
ST	3	-0.03	4/3	0.02	10	1/512	8	4.60	1.01 ± 0.09
SS	3	-0.03	4/3	0.02	9	1/256	3	9.24	1.01 ± 0.12

The combination of parameters that I varied, together with some results are summarised in Table 1. The first letter in the model designation indicates the Mach number and the strength of the gradient: I, J, and S have $\varepsilon_\mathrm{v} = 0.03$, while K, L, and R have $\varepsilon_\mathrm{v} = 0.2$. The second letter specifies the size of the accretor: M (medium) and S (small) stand for accretor radii of 0.1 R_A, and 0.02 R_A, respectively. I basically simulated models with all possible combinations of two relative wind flow speeds (Mach numbers of 3 and 10), two gradient strengths (3% and 20%) and two different accretor sizes (0.02 and 0.1 accretion radii), all with an adiabtic index of 5/3.

2. Results

Assuming a vortex flowing with Kepler velocity V just above the accretor's surface with radius $R_\star$, the specific angular momentum of such a vortex is

$$l_\mathrm{s} = R_\star V = \sqrt{R_\star/R_\mathrm{A}}\,\mathcal{M}_\infty R_\mathrm{A} c_\infty/\sqrt{2} \quad . \tag{1}$$

https://doi.org/10.1017/S0252921100042676 Published online by Cambridge University Press

Although for short periods of time the specific angular momentum can exceed l_s, it is difficult to imagine how accreted matter can *on average* (temporal) exceed this value. This implies that smaller objects (smaller $R_\star$) can accrete only smaller specific angular momenta, which goes to zero like $\sqrt{R_\star}$.

Giving the velocity of the surrounding medium a gradient of

$$v_{x\infty} = v_0 \left(1 + \varepsilon_v \frac{y}{R_A}\right) \quad , \tag{2}$$

and assuming that all angular momentum within the deformed accretion cylinder is accreted, then the specific angular momentum of the accreted matter follows to be (Ruffert, 1996; Ruffert & Anzer 1994; Shapiro & Lightman 1976; to lowest order in ε_v)

$$j_z = \frac{3}{2}\varepsilon_v v_0 R_A \quad . \tag{3}$$

R_A is the accretion radius.

In Fig. 1, I plot for several models the numerically obtained quantities l_z along with the amplitude of the fluctuations (one standard deviation, σ_z). These are plotted in units of l_s (Eq. (1)). Additionally, above the diamonds denoting the above mentioned ratio l_z/l_s, I plot, using plus-signs and squares the values that one expects from the analytical estimates.

Several trends can easily be noticed in Fig. 1. Model JM seems to be well below the general trend, indicating that the simulation was not evolved for long enough; I will not include this model in the following discussion. The four "K" and "L" models form a fairly homogeneous group accreting roughly 0.3 of the Kepler specific angular momentum. For the "I"- and "J"-models this fraction is roughly 0.1, thus confirming that for models with smaller gradients, the vortex around the accretor is less pronounced. These two groups vary less among themselves than the variation one would expect if the analytical estimates Eq. (3) (plus signs or squares) were valid. Thus, when estimating the specific angular momentum one should be guided by the Kepler-values Eq. (1). When applying Eq. (3) one should bear in mind the allowable parameter range: small gradients, supersonic flow and small accretors.

The smaller lever arm acting in models with smaller accretors is included in Eq. (1). Still, the "S"-cases have a slightly smaller value of l_z/l_s compared to the "M"-cases. The reduction is, however, not uniform for all models; the models with large gradients show reductions of at most a factor of 2, while the other models have a factor of 3. So small accretors impede high specific angular momentum accretion in some additional way than only via their smaller lever arm. At the distance of the surface (= radius of the accretor), matter seems to move in eddies at some fraction of the Kepler-speeds. This fraction is dependent more on the velocity gradient ε_v than on the size of the accretor or the Mach number.

Movies in mpeg format of the dynamical evolution of some models are available in the WWW at `http://www.mpa-garching.mpg.de/~ mor/bhla.html`

Acknowledgments. The Travel to the Conference was funded in part by the Deutsche Forschungsgemeinschaft.

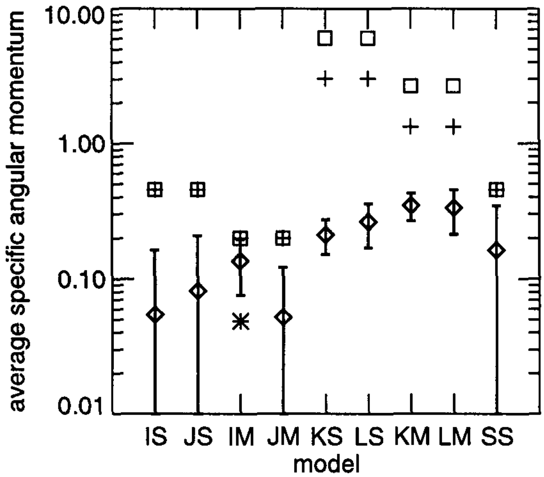

Figure 1. The average specific angular momentum (units: l_s, as given by Eq. (1)) is shown for most models by diamond symbols. The "error bars" extending from the symbols indicate one standard deviation from the mean. The long error bars extending to the bottom axis are an indication that the fluctuations of the respective model are so large, that the specific angular momentum changes sign from time to time. The plus signs above the diamonds indicate the specific angular momentum j_z according to the Shapiro & Lightman (1976) prescription, Eq. (3), while the squares denote the values j_z taken from a semi-numerical estimate. All models have $\gamma = 5/3$, except for model SS ($\gamma = 4/3$). The star ($*$) at the position of IM is the value taken from Ishii et al. (1993)

References

Berger M.J., Colella P., 1989, JCP 82, 64
Bondi H., Hoyle F., 1944, MNRAS 104, 273
Colella P., Woodward P.R., 1984, JCP 54, 174
Davies R.E., Pringle J., 1980, MNRAS 191, 599
Dodd K.N., McCrea W.H., 1952, MNRAS 112, 205
Hoyle F., Lyttleton R.A., 1939, Proc. Cam. Phil. Soc. 35, 405
Illarionov A.F., Sunyaev R.A., 1975, A&A 39, 185
Ruffert M., 1994, A&AS 106, 505
Ruffert M., 1996, A&A, in press
Ruffert M., Anzer U., 1995, A&A 295, 108
Shapiro S.L., Lightman A.P., 1976, ApJ 204, 555
Wang Y.-M., 1981, A&A 102, 36

Discussion

S. Chakrabarti: In our own galactic center, matter is supposed to be supplied from a set of stars placed on one side of the putative black hole. Would you comment on the angular momentum matter deposition on our galactic center?

M. Ruffert: I cannot comment in detail about applying my simulations to the galactic center, since my time is up. However I am sure that Fulvio Melia will do so in his talk.

H. Zinnecker: Do you plan to go to the next step of sophistication and include various radiation fields of the gravitational accretor?

M. Ruffert: Yes, but not in the short term. Including more physical processes is very important for comparison with "real" astrophysical objects. However, the numerics are still a challenge.

https://doi.org/10.1017/S0252921100042676 Published online by Cambridge University Press