Hunting for Hypervelocity Star Ejection Near a Super Massive Black Hole

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I have written some software in C ‘binary.c’ which requires the following libraries:

1) REBOUND Version 4.4.10 (NOT THE LATEST VERSION 5.x)
2) REBOUNDX

This software expects TWO input files:

A) ‘init_data.txt’
B) A file specified as a command line argument, e.g. ‘indata.txt’

The ‘binary’ software first reads in the simulation set-up data from file (A).

```
4.0e8
4.0e8
5e5
IAS15
15.0
B1
M 4e6
B2 relative to B1
M 1.0
a 112274.8
e 0.998667555
i 0.0
O 0.0
o 0.0
f -110.0
B3 relative to B2
f 0.0
M 1.0
e 0.0
a 1.0
i 0.0
O 0.0
o 0.0
```

The format of file (A) is shown in FIGURE (1). This Figure assumes all the orbital parameters are specified for bodies ‘B2’ and ‘B3’, though in pracitice it is only ‘B2’ which needs to be fully specified. Body ‘B1’ is the SMBH at the centre. Note that ‘B2’/’B3’ is the binary pair of stars. The software at the moment is very intolerant of input data faults so please conform to this layout for bodies ‘B1’ & ‘B2’.

The first row is the maximum duration of the simulation in seconds. The simulation is separated into segments and the time duration of each segment is given by the second row. In this case there is only one segment. This is essentially the frequency with which the bodies ‘B2’ and ‘B3’ are checked for having a positive energy AND radial velocity w.r.t. body ‘B1’ (the SMBH). If either of these bodies satsify both these criteria, the simulation is stopped. Note this is NOT the simulation time-step.

Row three is the exit radius in millions of km – this specifies that the simulation should stop if any body reaches this distance from the CoM (in this case to-all-intents-and-purposes, the centre of the SMBH).

There are two choices for integration method 'IAS15' (row 4) where the software auto-adjusts the simulation time-step over the course of the integration, and 'WHFAST', where the time-step is constant and must be provided by the user on the following line. In either case the next line (row 5) must specify the simulation time-step, for 'IAS15' this is for initialization purposes only.

'B1' indicates the subsequent data should be for SMBH (only mass [M] is needed).

'B2' indicates the subsequent data is for the first of the binary stars

'B3' indicates the subsequent data is for the the second of the binary stars.

```
'a' = semi-major axis (Millions of km)
'e' = eccentricity
'i' = inclination (deg)
'O' = ascending node (deg)
'o' = argument of periapse (deg)
'f' = true anomaly (deg)
'M' = Mass in Solar Masses
```

FIGURE (2) Parameter Defs, file (A)

'B2' should ALWAYS be fully specified. 'B3' need not be fully specified but in this example it is.

We have for both of these bodies, the definitions given in FIGURE (2). Note that the file (B) contains all the outstanding parameters for 'B3' that are NOT contained in file (A). The software expects the order of the data in (B) to conform to that given in FIGURE (2). If ALL of the parameters are specified for 'B3' in file (A), then the file (B) should be empty.

Thus file (B) fills in the outstanding parameters for body 'B3' which are absent in file (A). The values in (B) have the same units as those in FIGURE (2), though have NO preceding parameter indicator (such as 'a' or 'e' etc).

The logic behind this set-up is as follows.

Having input all the data (A) and (B) 'binary' performs an integration forwards in time until either:

(a) the maximum time (specified in (A)) is reached
(b) one particle has exited the simulation as specified by the exit radius, also in (A)
(c) the semi-major axis becomes negative and the radial velocity is positive for either 'B2' or 'B3', both w.r.t. 'B1'.

It then outputs a single number based on the 'characteristic energy', C_3, of body 'B2' or 'B3' (whichever is the larger), in units of km^2s^{-2}, w.r.t the SMBH (body 'B1'). The value of C_3 is defined as follows:

$$C_3 = -\frac{GM_{B1}}{a_{B*/B1}}$$

Where GM_{B1} is the gravitational mass of the SMBH, and $a_{B*/B1}$ is the semi-major axis of either 'B2' or 'B3' w.r.t. the SMBH ('B1'), whichever is the lowest

If ejection of 'B*' has been accomplished, then C_3 will be positive and the square root will be the hyperbolic excess speed of 'B*' relative to 'B1' in kms^{-1}.

IT SHOULD BE NOTED THAT IN FACT 'binary' OUTPUTS THE NEGATIVE OF THE CHARACTERISTIC ENERGY GIVEN ABOVE, SO THAT AT EJECTION THE OUTPUT WILL ALWAYS BE NEGATIVE.

Thus in fact the output of 'binary' is:

$$Output = \frac{GM_{B1}}{a_{B*/B1}}$$

The reason for this is to do with why the input data is split into 2 files ((A) & (B)).

What we wish to do is find the values of the parameters in file (B) which maximise the speed of escape (actually the hyperbolic excess) of 'B*' so that C_3 is as LARGE AS POSSIBLE, this is precisely what the purpose of NOMAD is. However NOMAD is a minimizer NOT a maximizer, thus we need to switch the sign of C_3 in order for NOMAD to find a maximum as opposed to the minimum.