

EVOLUTION AND FRAGMENTATION OF MASSIVE PROTOSTELLAR DISCS WITH VARIABLE COOLING RATES

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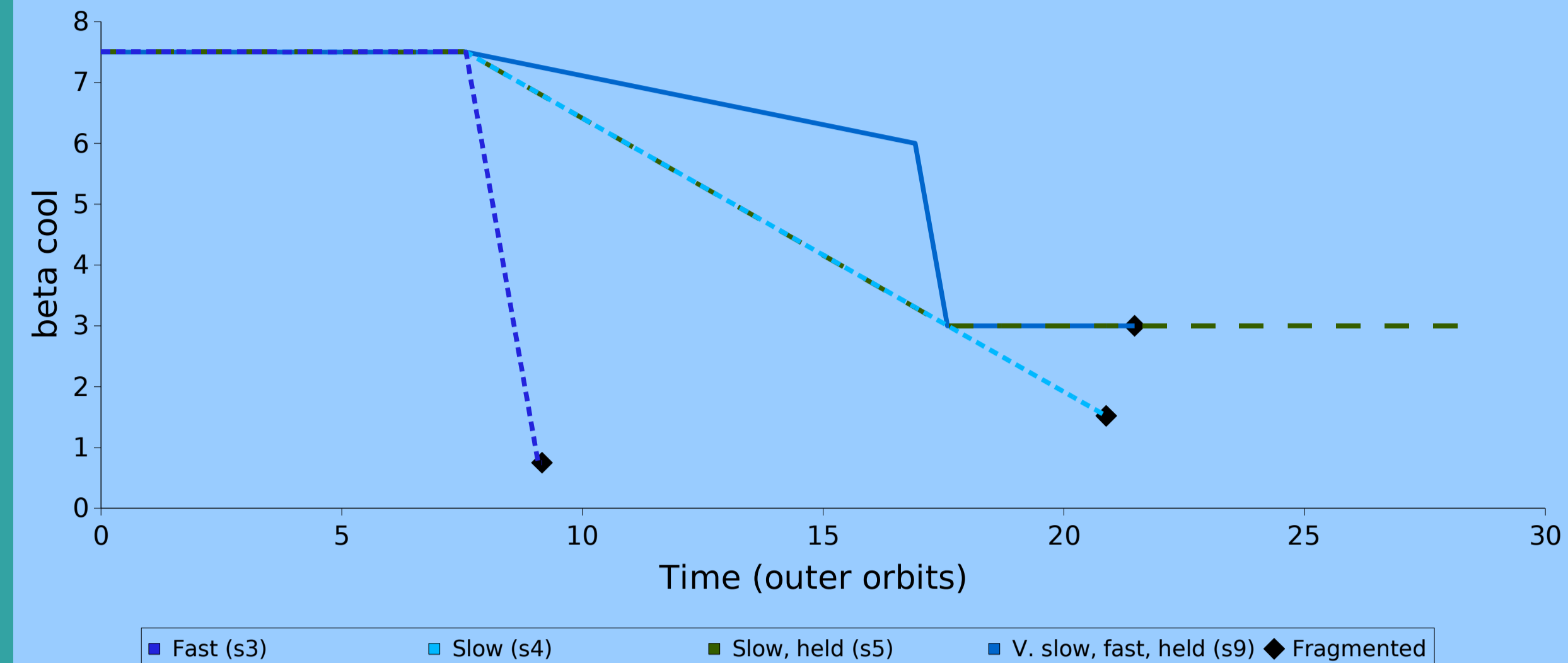


Aim: To test how the variation of cooling rates affects the subsequent fragmentation of an accretion disc due to gravitational instabilities. To investigate how different gradients of cooling rate affects resistance to fragmentation and looks at the results obtained with different histories and resolutions.

Introduction:

Planets are thought to form in accretion discs around young stellar objects. The standard core accretion theory requires a few million years to form Jupiter like planets, probably more than the typical disc lifetime (Haisch et al. 2001, Briceno et al. 2001). The alternative Gravitational Instability model could resolve this (Boss 2000) forming Jupiter like planets directly from disc fragmentation in a relatively short time. Discs which are cold enough are gravitationally unstable but the compression and shocks formed from the instability heat up the disc and prevents fragmentation (Goldreich & Lynden-Bell 1965). Thus, the cooling rate must be fast to overcome the heating and fragment the disc. Simulations suggest the critical cooling time is between 3 and 5 Ω^{-1} (Rice et al. 2005, Gammie 2001). However, these results are generally obtained from simulations which employed a time independent cooling rate, whereas the thermal properties of the disc are expected to vary with time. We therefore run simulations where $\beta_{cool} = t_{cool} * \Omega = \beta_{cool}(t)$, to check the importance of thermal history in fragmentation. We find that if beta is varied slowly from a stable value to a potentially unstable one, the disc is more resistant to fragmentation.

Graph Showing Different Cooling Rate Gradients

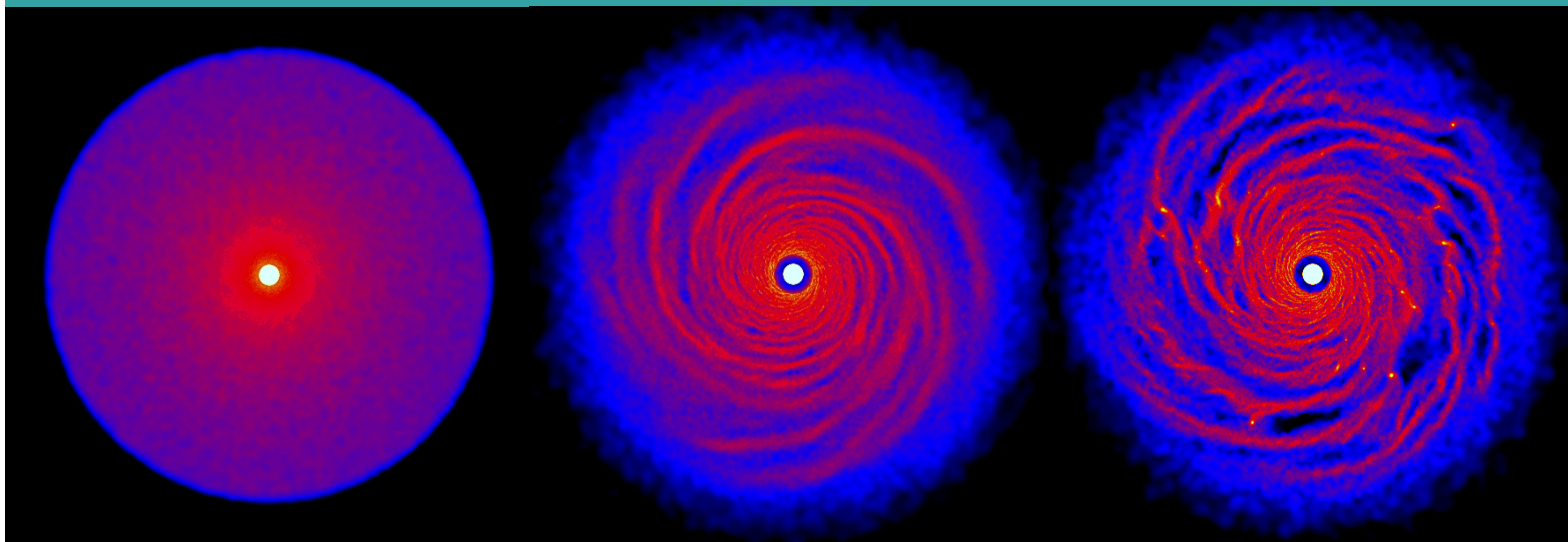


Run	Initial β_{cool}	Final β_{cool}	No. O. Orbits	Gradient	Fragmented?
S3	7.50	0.75	1.50	Fast	Yes
S4	7.50	1.52	13.30	Slow	Yes
S5	7.50	3.00	10.00	Slow	No
S6	7.50	2.75	10.56	Slow	No
S7	7.50	2.62	10.84	Slow	Yes
S8	7.50	2.50	11.12	Slow	Yes
S9	7.50	6.00	9.33	V. Slow	Yes
	6.00	3.00	0.67	Fast	
	3.00	3.00	3.89	Null	Yes

Left: Table of the main simulation run. All times in outer orbits = orbital period at $R=25$.

S1 and S2 were identical to S3 and S4 but from less stable initial disc.

Higher resolution simulations were run with identical conditions as S4 and S5.



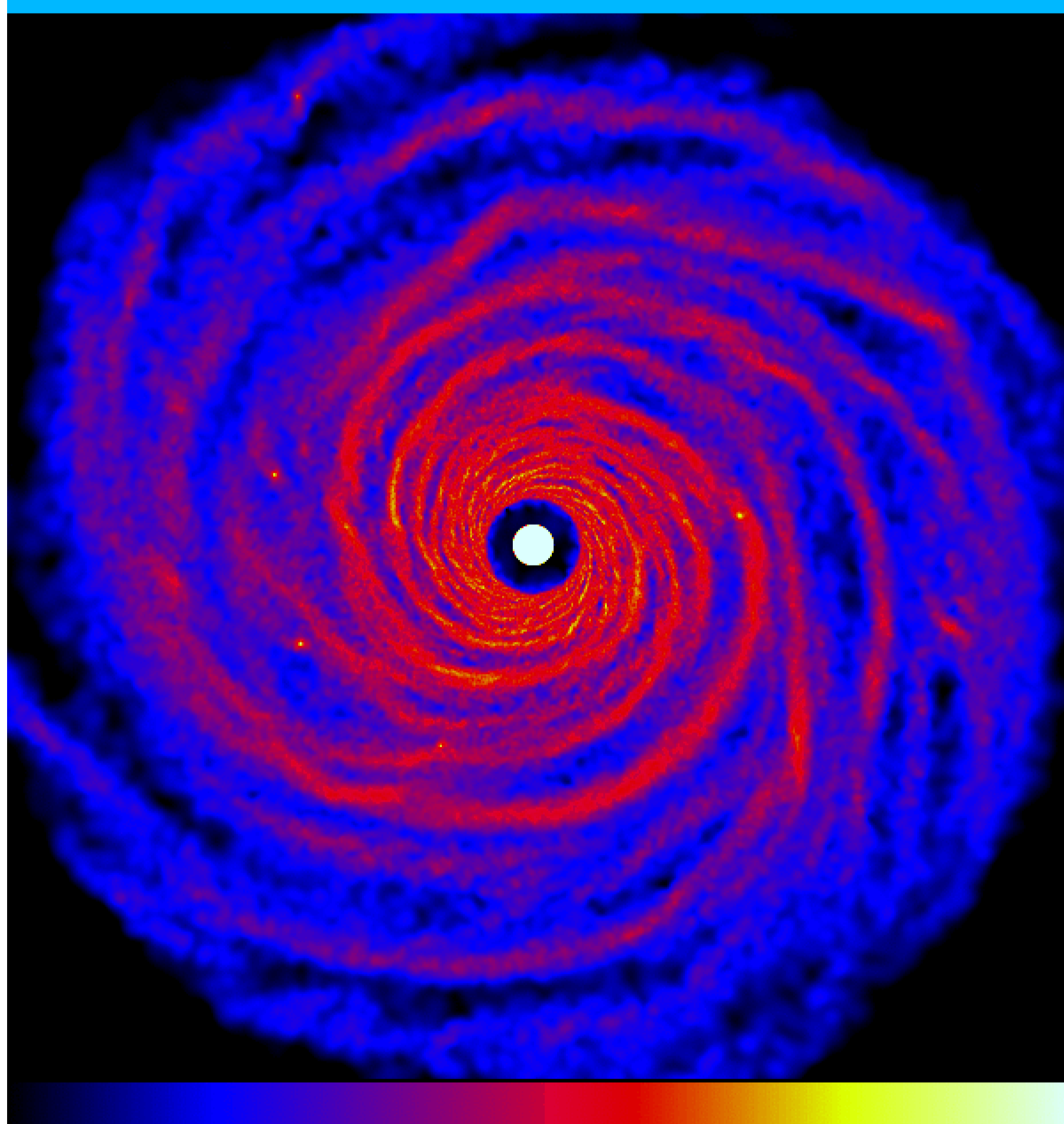
Time = 0
warm, axis symmetric disc

Time = 7.58 outer orbits
marginally stable disc

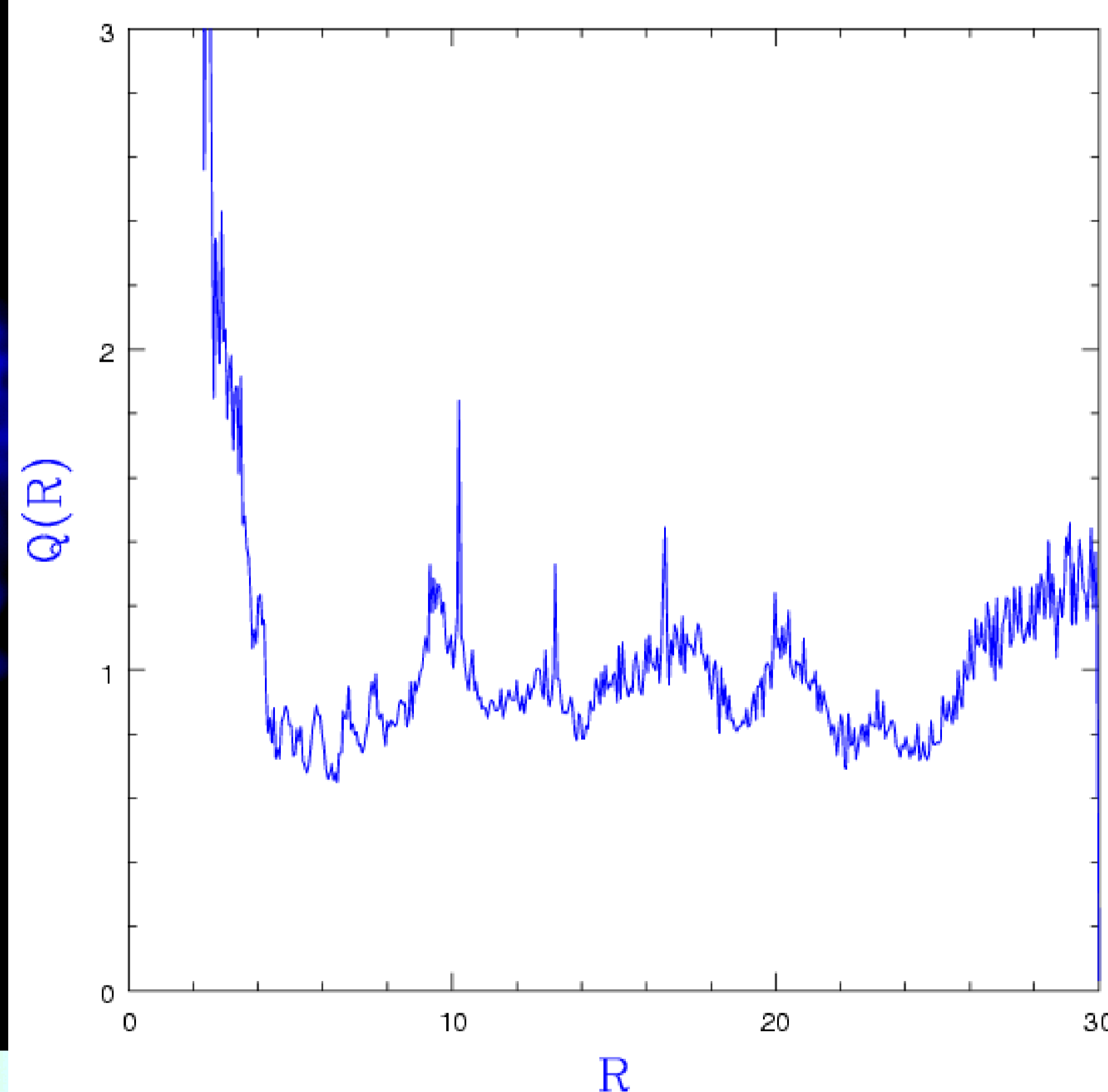
Time = 9.16 outer orbits (run s3)
Fragmented disc

Details of simulation:

Smoothed Particle Hydrodynamic model of full 3D disc (very similar to Rice et al. 2003, Lodato and Rice 2004, 2005). The disc is represented by 250 000 particles (500 000 for higher resolution simulations). The disc extends from radius 0.25 to 25 code units and the accretion radius is 0.25. The star has mass of 1 code unit and the disc mass is 0.1 code units.

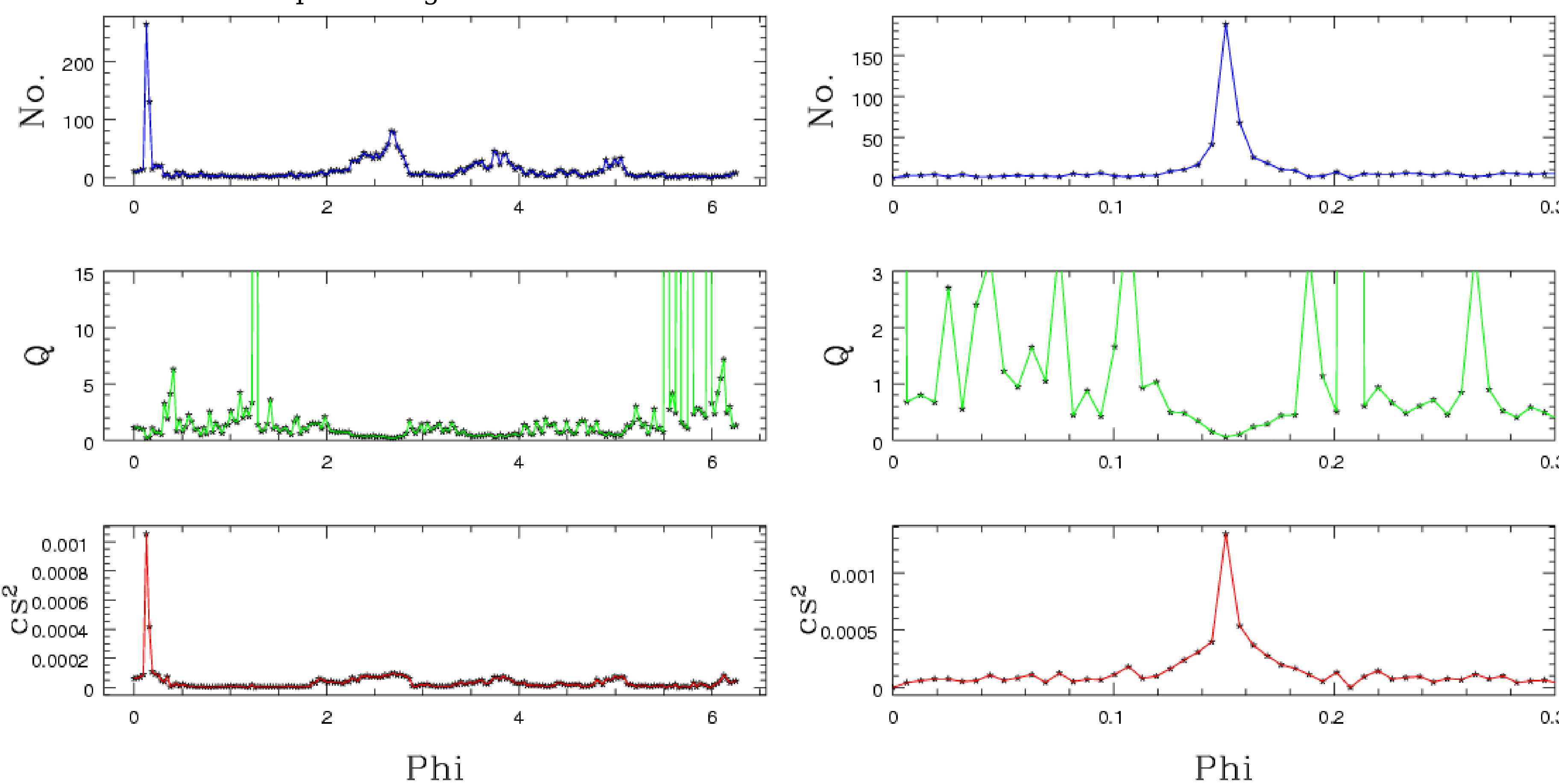


Above: image of S4 after 20.8 outer orbits (image is 60 code units wide and high)



Above: Azimuthally averaged radial Q profile for the disc

Below: Graphs of angular distributions for an annulus between $10.13 < R < 10.33$ of the above disc



Additional Results:

Resolution – Previous work suggests an increase above 250 000 particles does not give significant results. This work shows that the small increase in sensitivity gained from increased resolution may make the simulation more accurate when making more gradual changes in β_{cool} .

Effect of fragment – as can be seen in the graphs bottom left as a fragment forms the heat released due to gravitational collapse heats up the surrounding disc stabilising it against fragmentation.

Equations:

$$Q = \frac{c_s \kappa}{\pi G \Sigma}$$

(Toomre 1964)

c_s = sound speed
 κ = epicyclic frequency
 Σ = surface density

$Q > 1$ – stable
 $Q < 1$ – unstable

$$\beta_{cool} = \frac{t_{cool}}{t_{dyn}}$$

t_{cool} = cooling time
 $t_{dyn} = \Omega^{-1}$ = dynamical time

Conclusions:

For the first time simulations have been run that do not start from an unstable cooling rate but approach it more realistically.

These results confirm that a disc fragments when it is required to balance a large cooling rate.

There is a suggestion that the disc might be more resistant to fragmentation when driven slowly towards the fragmentation threshold. A slower change in β_{cool} results in more resistance to fragmentation with fewer fragments forming at lower values of β_{cool} and taking longer to form.

It is possible that an explanation for this is in the modes excited within the spiral structure of the disc, as β_{cool} changes more slowly the disc has time to adjust modes to the new stable modes. However, more work is needed to investigate this as no significant change was seen to be relevant.

When a fragment forms it releases heat into the surrounding material and prevents more clumps forming around it.

Further work:

An investigation of other gradients would be interesting to see how the critical value of β_{cool} varies for different cooling rate increases.

To study how sensitive the discs are to the critical value repeated full runs of the same simulations would be interesting to see when and where the fragments form.

It is important to test these results with a different code (e.g. ZEUS) to see if the same results are obtained or if it is just a feature of the code.

It would be interesting to model the curves of β_{cool} in different ways, such as smoother curves, to see how this affects the fragmentation.

Higher resolution runs are needed of all of the simulations to see if differences seen between the 500 000 particle and 250 000 particle runs are significant.

References:

- Boss A P, 2000, ApJ 536:L101
- Briceno C, Vivas A, Calvet N, Hartmann L, Pacheco R et al. 2001, Science, 291:93-6
- Gammie C F, 2001, ApJ 553:174
- Goldreich P, Lynden-Bell D, 1965, MNRAS, 130:130-125
- Haisch K E, Lada E A, Lada C J, 2001, Ap. J. Lett. 553:L153-6
- Lodato G, Rice W K M, 2004, MNRAS, 351:630
- Lodato G, Rice W K M, 2005, MNRAS, 358:1489
- Rice W K M, Armitage P J, Bate M, Bonnell I A, 2003, MNRAS, 339:1025-30
- Rice W K M, Lodato G, Armitage P J, 2005, MNRAS 364:L56-60
- Toomre A, 1964 ApJ 139:1217