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Erratum: Collapse of a molecular cloud core to stellar densities: stellar core and outflow formation in radiation magnetohydrodynamics simulations

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The paper 'Collapse of a molecular cloud core to stellar densities: stellar core and outflow formation in radiation magnetohydrodynamics simulations' was published in MNRAS, 437, 77 (2014) (hereafter 'the Original Paper').

The calculations presented in that work were performed using a smoothed particle magnetohydrodynamics code known as `sphNG`. Unfortunately, a bug was present in the integrator that was used to evolve the magnetic field. This necessitated the use of rapid divergence cleaning of the magnetic field (using a cleaning speed 30 times faster than the fast magnetohydrodynamics, MHD, wave speed) in the Original Paper in order to maintain stability of the calculations. We are grateful to Dobbs (private communication) for the discovery of the error in the integrator.

In this erratum, we compare results from one of the original calculations with those obtained using a more recent version of the code in which the integrator has been corrected. In addition, the more recent code includes the improved divergence cleaning scheme of Tricco, Price & Bate (2016), though we have found that for this problem, the differences between calculations using the older cleaning scheme and those using the new scheme are insignificant. The corrected code uses the standard divergence cleaning wave speed (equal to the fast MHD wave speed). This allows larger time-steps to be taken, which results in the calculations running up to 30 times faster early on. However, after the stellar core forms, the calculations are only about four times faster because thermal and gravitational forces dominate over magnetic forces inside the stellar core. We show that the results of the calculations are slightly different, but these minor differences do not affect the conclusions in the Original Paper.

Section 1 of this erratum discusses the integrator bug in detail and then in Section 2, we provide a side-by-side comparison of the calculation from the Original Paper that had the strongest magnetic field strength with a calculation using the more recent code that uses a corrected integrator and includes the improved divergence cleaning scheme.

1 THE INTEGRATOR BUG

We use a two-stage second-order Runge–Kutta–Fehlberg integrator (RK1(2) in Fehlberg 1969) to evolve all fluid parameters (e.g. velocity), except the density[1], in time. This integrator can be represented for an arbitrary quantity, φ as

$$\varphi_{t+1/2} = \varphi_t + \frac{\Delta t}{2}\dot{\varphi}_t \tag{1}$$

for the first half of the time-step, Δt, and

$$\varphi_{t+1} = \varphi_t + \frac{1}{256}\dot{\varphi}_t \Delta t + \frac{255}{256}\dot{\varphi}_{t+1/2}\Delta t \tag{2}$$

for the complete time-step. In the Original Paper and all earlier papers using `sphNG`, this was implemented correctly for all fluid quantities except for the magnetic field vector, B^i. There, instead of the second term on the right-hand side of equation (2) being

$$\frac{1}{256}\left.\frac{\partial B^i}{\partial t}\right|_t \Delta t, \tag{3}$$

the value from when $t = 0$ was erroneously retained, in effect, replacing this term by

$$\frac{1}{256}\left.\frac{\partial B^i}{\partial t}\right|_0 \Delta t. \tag{4}$$

Superficially, this appears to be very serious; however, several factors conspire to make the resulting error small. First, the initial conditions for the calculations in the Original Paper are such that at $t = 0$, the rate of change of the magnetic field is very small. Secondly, the second term on the right-hand side of equation (2) only contributes at the level of $1/256 \approx 0.5$ per cent to the magnetic field evolution. Thirdly, whenever the code was stopped and restarted, this term was updated using the value of $\partial B^i/\partial t$ at restart. Due to the gravitational collapse, the calculations require more computational time as the collapse proceeds and due to the queuing system on the compute cluster, they were stopped and restarted frequently (≈20 times for each calculation).

2 COMPARISON OF CALCULATIONS

To demonstrate that the correction of the integrator bug (and the other changes to the code) have only minor effects on the calculations reported in the Original Paper, here we compare the results of one of the calculations from the Original Paper with a new calculation using the updated code, including the correct integrator. We will refer to the former as the '2014' calculations and the latter as the '2016' calculations. We chose the calculation with the strongest

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[1] This is set self-consistently with the smoothing length such that $h \propto 1/\rho^{1/3}$

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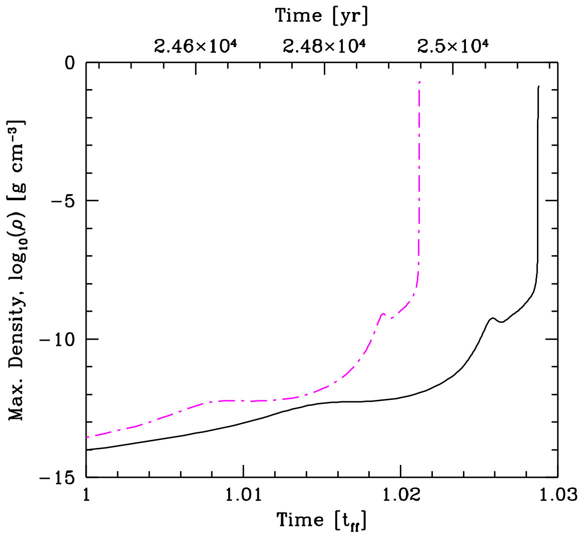

Figure 1. The time evolution of the maximum density during the radiation magnetohydrodynamical calculations of a collapse of molecular cloud cores with an initial mass-to-flux ratio of $\mu = 5$. The free-fall time of the initial cloud core, $t_{\rm ff} = 7.71 \times 10^{11}$ s (24 430 yr). The results from the Original Paper using an incorrect integrator (‘2014’) are plotted using a magenta dot–dashed line, while those obtained using the correct integrator (‘2016’) are plotted using the solid black line. The new calculation takes 0.7 per cent longer to collapse, but once the collapse accelerates the evolution is almost identical.

initial magnetic field strength (mass-to-flux ratio $\mu = 5$) since this is the calculation in which the magnetic field has the strongest effect; the effects on calculations with lower field strengths should be even more minimal.

The 2016 calculation takes very slightly longer (0.7 per cent) to collapse than the 2014 calculation (see Fig. 1). This is because the time-steps are larger (since the fast divergence cleaning is not required) that in turn results in the radiative cooling of the core not being calculated as accurately, leading to the gas being up to 2 K warmer during the initial cold collapse phase (see the left-hand panel of Fig. 2). We have confirmed that this is improved if the time-steps are reduced, but this is unnecessary since it is the high-density evolution in the latter part of the calculation that we are interested in and this late evolution is not affected by a small delay in the early collapse.

In Fig. 3, we display density and temperature snapshots of the first hydrostatic core and outflow from the Original Paper and from the new calculation (bottom panels of Figs 4 and 5 in the Original Paper). In Fig. 4, we display density and temperature snapshots of the stellar core and outflow from the Original Paper and from the new calculation (bottom panels of Fig. 10 in the Original Paper). It can be seen that the structures of the first hydrostatic core, the stellar core, and the two outflows are very similar between the two calculations. This also applies to other quantities discussed in the Original Paper, with the exception of the maximum field strength obtained in the stellar core. In the right-hand panel of Fig. 2, we plot the evolution of the maximum magnetic field strength as a function of the maximum density for the two calculations. The two are very similar, except after the stellar core has formed ($\rho > 0.005$ g cm^{-3}) when the artificial resistivity in the new calculation produces a more rapid decay of the magnetic field than in the original calculation. As demonstrated in Fig. 21 of the Original Paper, this decay of the field inside the stellar core is artificial and depends noticeably on resolution (with higher resolution resulting in slower rates of decay), but it is more rapid with the corrected integrator. We have confirmed that this difference comes from the correction of the integrator bug alone – running a new calculation with a code that includes the integrator bug gives a slower decay of the field in the stellar core. The difference between the maximum field strength obtained in the 2014 calculation and that obtained in the 2016 calculation is approximately a factor of 3.

In summary, despite the presence of the error in the integrator used for the calculations presented in the Original Paper (Bate, Tricco & Price 2014), all the main conclusions of the paper remain valid and the error had no substantial effect on the results presented in the Original Paper. In particular, the density, temperature, and magnetic structures discussed in the Original Paper are almost identical to those obtained with the corrected and updated code.

The data set consisting of the output and analysis files from the new calculation presented here have been placed in the University of Exeter’s Open Research Exeter repository, and can be accessed via the handle: http://hdl.handle.net/10871/24463.

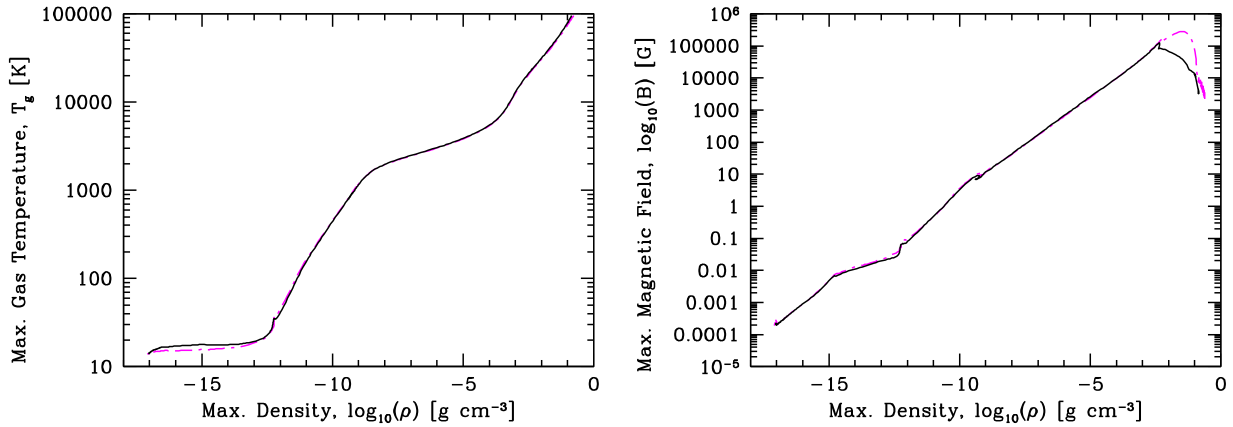

Figure 2. The evolution of the maximum gas temperature (left) and maximum magnetic field strength (right) versus maximum density for the RMHD calculations of the collapse of rotating molecular cloud cores with an initial mass-to-flux ratio of $\mu = 5$. The results from the Original Paper using an incorrect integrator (‘2014’) are plotted using a magenta dot–dashed line, while those obtained using the correct integrator (‘2016’) are plotted using the solid black line. Gas is slightly warmer early in the new calculation because of the use of larger time-steps for the integration. After the stellar core forms, the artificial resistivity produces a more rapid decay of the magnetic field inside the stellar core.

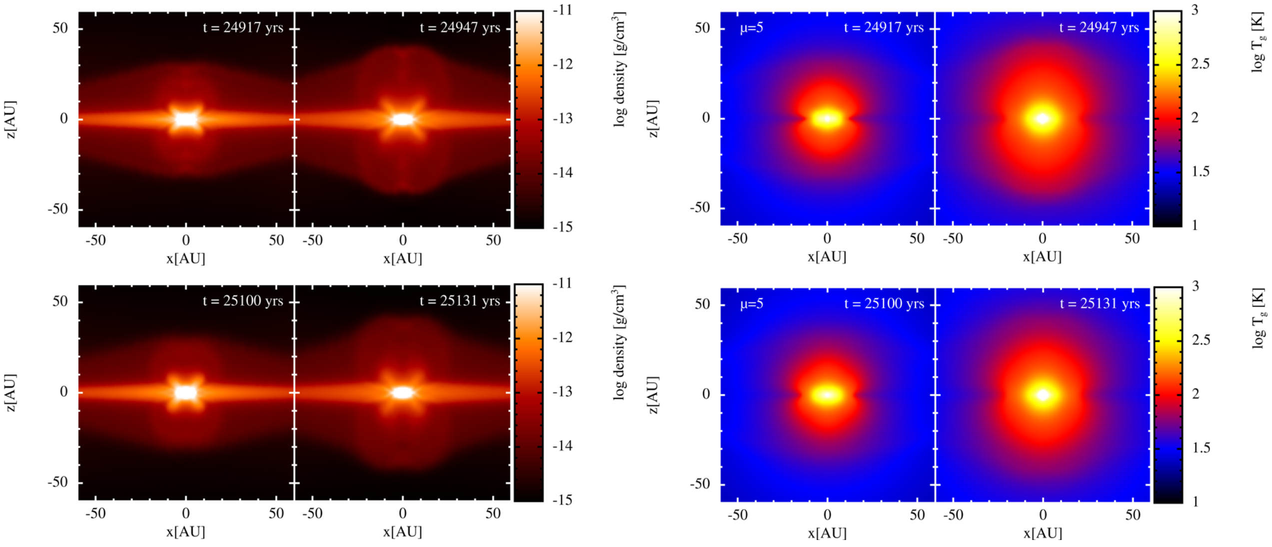

Figure 3. Comparison between results obtained using the incorrect integrator (‘2014’, top panels), compared with those obtained using a correct integrator (‘2016’, lower panels). Each pair of panels gives a cross-section of the density or temperature at two times: when the maximum density is 10^{-9} (left) or 10^{-7} (right) g cm^{-3}. The initial conditions had a mass-to-flux ratio $\mu = 5$. There are some very small differences in the structure of the outflow from the first hydrostatic core between the old and new calculations. In particular, in the 2014 calculation, there is some weak density structure along the axis of the outflow that is not present in the 2016 calculation. However, apart from this, the outflows produced have almost identical speeds and morphologies.

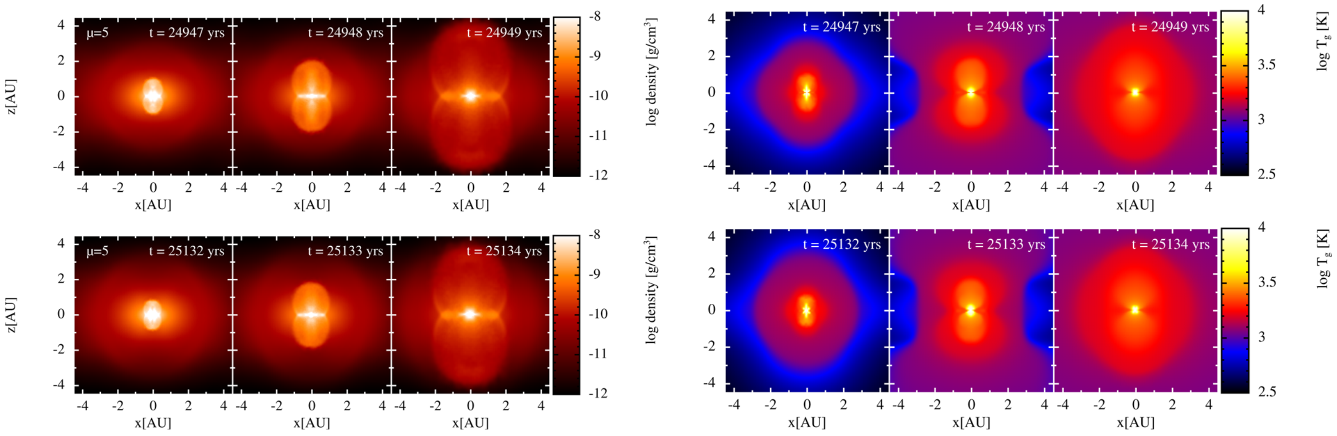

Figure 4. Comparison between results obtained using the incorrect integrator (‘2014’, top panels), compared with those obtained using a correct integrator (‘2016’, lower panels). Each triplet of panels gives a cross-section of the density or temperature at three times from left to right: 0.5, 1.0, and 2.0 yr after the formation of the stellar core (defined as being when the maximum density first exceeds 10^{-4} g cm^{-3}). The initial conditions had a mass-to-flux ratio $\mu = 5$. The density and temperature structure of the outflows from the stellar core are almost identical for the two calculations.

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