Influence of thermonuclear effects on the collapse of supermassive stars

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Outline of the talk

➢ Introduction and astrophysical motivation
➢ Nada GRHydro code, EOS and nuclear burning
➢ Results
➢ Conclusions
Introduction

• Large observational evidence: MBH exist in the centre of most nearby galaxies (e.g. orbital motion of stars in Sgr-A* suggest MBH~4x10^6M_ʘ)

Observation of luminous quasars at z ≥6 in the SDSS implies that SMBH with masses ~10^9M_ʘ which are believed to be the central engine of such powerful quasars were formed within the first billion years after Big-Bang

Still unknown: How SMBH form and grow to such high masses in such a short time

➢ Different routes based on stellar dynamical processes, hydrodynamical processes or a combination of both have been suggested

a) One theoretical scenario for SMBH seed formation is the gravitational collapse of the first generation of stars (Pop III) with masses ~100 M_ʘ

Expected to form in halos with virial temperature T_{vir} <10^4K, at z~20-50 where cooling by molecular hydrogen is effective (Haiman&Loeb 2001; Yoo&Miralda-Escude 2004)
Introduction

b) Another possible scenario proposes that if sufficient gas is unable to cool below $T_{\text{vir}} \sim 10^4 \text{K}$, a supermassive star (SMS) with mass $>5 \times 10^4 M_\odot$ may form, and such object would eventually collapse to a SMBH, thus it is a substantial jump towards its growth to $10^9 M_\odot$.

- This route assumes that fragmentation and cooling are suppressed by the presence of a UV radiation field that prevents the formation of molecular hydrogen.

- In addition, Omukai et al. (2008) found that fragmentation may be suppressed if the environment metallicity is $<10^{-4} Z_\odot -10^{-6} Z_\odot$.

- If gas accumulation in these DM halos proceeds at low rate, isentropic SMSs could form and evolve as equilibrium configurations dominated by radiation pressure (Iben 1963, Hoyle & Fowler 1963, Fowler 1964).

- Alternatives for SMSs formation have been suggested: i.e. Supermassive dark matter stars (Spolyar et al 2008, Freese et al 2010), and non-isentropic SMSs by Begelman (2009).

Rest of the talk will focus on the evolution of collapsing isentropic SMSs.
Main properties of SMSs

- These are equilibrium configurations with masses ranging $10^4 \ M_\odot - 10^8 \ M_\odot$ mostly supported against gravitational collapse by radiation pressure.

- Gas pressure is only a minor contribution to the EOS

\[ \Gamma_{SMS} \approx \frac{4}{3} + \frac{\beta}{6}, \text{ where } \beta = \frac{P_g}{P_r} \ll 1 \]

- Plasma correction and GR effect are small though cannot be neglected for the evolution

- GR lead to the existence of a maximum for the equilibrium mass as a function of the central density

Means that for a given mass there is a critical density for which configurations are dynamically unstable against radial perturbations (Chandrasekhar 1964)

\[ \rho_{\text{crit}} = 1.994 \times 10^8 \left( \frac{0.5}{\mu} \right)^3 \left( \frac{M}{M_{\text{sun}}} \right)^{-7/2} \ \text{gcm}^{-3} \]
Main properties of SMSs

SMSs shine at Eddington luminosity

Quasi-stationary phase of cooling and contraction as they radiate away their energy

Shrink and the central density increases until it reaches the critical density

Instability sets in and the collapse may lead to the SMBH formation

The stabilizing effect of the gas pressure does not rise sufficiently the adiabatic index to compensate for the destabilizing effect of GR

Baumgarte & Shapiro (1999): rotating SMSs at mass shedding limit at the point of the instability.
a) Simulations of spherical collapse:

- **Shapiro & Teukolsky (1979):** first 1D relativistic simulations of spherical collapse of SMSs, using a $\Gamma$-law EOS

- **Fuller, Woosley & Weaver (1986):** simulations of collapsing spherical SMS:
  - detailed thermonuclear reaction network (H and He burning)
  - detailed EOS including effect of electron-positron pairs
  - post-Newtonian treatment of gravity

Found that SMSs with masses $M > 10^5 M_\odot$ and initial metallicities $Z_{\text{CNO}} < 0.005$ do not explode while SMSs with larger metallicites do explode (hot-CNO cycle)
• Linke (2001): 1D spherical collapse with outgoing null foliation of spacetime, computed neutrino luminosities.

b) GR simulations of collapse of rotating stars:

Nuclear burning not included and Γ-law EOS

• Shibata & Shapiro (2002): indicated that about 90% of the initial mass ends up in the BH with a spin of about 0.75.

• Saijo & Hawke (2009): 3D simulations with Cactus+Whisky code, investigation of the GWs emission and provided waveforms of the non-axisymmetric collapse.
Importance of nuclear burning

Influence of the energy liberated through hydrogen burning during the collapse of a rotating SMSs?

- If $Z=0$, only proton-proton chain (pp-chain) and helium burning (triple-alpha) are possible.

- If $0<Z<Z_{\text{crit}}$ then CNO-cycle and hot-CNO cycle (at $T \leq 0.5 \times 10^9 \text{K}$) limited by the beta-decays of $^{14}\text{O}$ and $^{15}\text{O}$, become the main sources of nuclear energy release.

- At $T>0.5 \times 10^9 \text{K}$ the break-out of the hot-CNO cycle is possible via $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$ (rp-process).

Wallace & Woosley (1981)
2D axisymmetric code that solves the coupled system of Einstein equations and GRHD equations:

- BSSN formulation of Einstein eqs:
  - 4th order finite differencing
  - Cartoon method: axisymmetry using a Cartesian grid
  - Puncture approach for BH treatment

- GRHD eqs in conservation form:
  - HRSC schemes: Roe and HLLE solvers
  - Slope-limited TVD and PPM reconstructions

- Time integration using MoL: 4th-order RK scheme

PM, Font & Shibata, PRD (2008)
EOS:

➔ Contribution of baryons and radiation separately:

\[ P = \frac{1}{3} a T^4 + \frac{R \rho T}{\mu} \]

Use a table to take into account the electron-positron pair creation:

at \( T > 10^9 \text{K} \) part of the energy is used to create pairs and therefore reducing the adiabatic index below \( 4/3 \) and stability of the star.

➔ Temperature obtained by Newton-Raphson

➔ Neutrino losses due to:

➢ Pair annihilation (Itoh 1996)
➢ Photo-neutrino emission (Itoh 1996)
➢ Plasmon decay (Haft et al. 1994)
Nada code

**Nuclear energy generation rates:**

- Nuclear energy rates associated to: pp-chain, triple-alpha, CNO cycles and rp-process

In order to avoid the complexity and stiffness derived from the solution of the nuclear reaction network we follow an approximate method and take into account the net reaction energy release rate associated to the above processes as a function of density, temperature and mass fractions (H, He, CNO)

- We add these as a source term for the energy conservation equation

- Limitation: mass fractions remain fix during the evolution

\[
\frac{\partial e}{\partial t} = 4.4 \times 10^{25} \rho X_H Z_{CNO} \left[ \frac{\exp(-15.231/T_9^{1/3})}{T_9^{2/3}} \right] + \left[ 8.3 \times 10^{-5} \frac{\exp(-3.0057/T_9)}{T_9^{3/2}} \right] \text{erg g}^{-1} \text{s}^{-1}
\]
Uniform Cartesian grid in 2D (0<x,z<L)

The “regriding technique” (Shibata&Shapiro) to follow the evolution:

**Initial phase:**
- Rezone the computational domain
- Keep the number of grid points, NxN = 300x300, L=1200M
- Moving the outer boundary inward decreasing the grid spacing
- Repeat 3 times until the collapse timescale in centre is much shorter than in envelope

**Next:**
- 0.9>α >0.8, NxN= 600x600, L=400M
- 0.8>α >0.3, NxN= 1200x1200, L=200M
- 0.3>α , NxN= 1800x1800, L=60M
Initial models

Table 1. Main properties of the initial models studied and their fate. From left to right, the columns show: model name, gravitational mass, initial central rest-mass density, ratio of rotational to gravitational energy $T/|W|$, initial central temperature, metallicity, and outcome of the evolution.

| Model | $M_{\text{grav}}$ [$M_\odot$] | $\rho_c$ [g/cm$^3$] | $T/|W|$ | Temp [K] | Initial metallicity | Fate |
|-------|-------------------------------|---------------------|---------|---------|---------------------|------|
| S1.a  | $5.0 \times 10^5$             | $2.42 \times 10^{-2}$ | 0       | $5.8 \times 10^7$ | $2.0 \times 10^{-3}$ | BH   |
| S1.b  | $5.0 \times 10^5$             | $2.42 \times 10^{-2}$ | 0       | $5.8 \times 10^7$ | $4.0 \times 10^{-3}$ | Explosion |
| S1.c  | $5.0 \times 10^5$             | $2.42 \times 10^{-2}$ | 0       | $5.8 \times 10^7$ | $5.0 \times 10^{-3}$ | Explosion |
| R1.a  | $5.0 \times 10^5$             | $4.0 \times 10^{-1}$ | 0.0088  | $1.3 \times 10^8$ | $5.0 \times 10^{-4}$ | BH   |
| R1.b  | $5.0 \times 10^5$             | $4.0 \times 10^{-1}$ | 0.0088  | $1.3 \times 10^8$ | $8.0 \times 10^{-4}$ | Explosion |
| R1.c  | $5.0 \times 10^5$             | $4.0 \times 10^{-1}$ | 0.0088  | $1.3 \times 10^8$ | $2.0 \times 10^{-3}$ | Explosion |
Results collapse SMSs

Model S1.c, $Z=0.005$
- Central density at bounce
  - Nada code: 2.9 g/cm³
  - Fuller et al. (1986): 3.1 g/cm³
- Central temperature at bounce
  - Nada code: 2.6x10⁸ K
  - Fuller et al. (1986): 2.6x10⁸ K

Collapse to BH
Thermal bounce

Log($\rho_c$) [g/cm³]

Log(t) [K]

Log(t) [K]
Results collapse SMSs

Fig. 4—Nuclear energy generation rate (ergs s$^{-1}$) is shown for the stellar model in the previous figures as a function of time (in units of 10$^4$ s) from the instability point. Nuclear energy generation is due entirely to hydrogen burning on the CNO cycle. The temperature during the collapse shown here is not high enough to trigger copious neutrino emission. The result is that the integrated thermal energy released by the hydrogen burning depicted here is $\sim 10^{50}$ ergs, which is eventually mostly converted to the kinetic energy of the explosion.
We find that the central density and temperature at the thermal bounce are 2.9 g/cm$^3$ and 2.6x10$^8$ K respectively.

This in good agreement with results of Fuller et al. (1986) and difference is of a few percent.

The thermal bounce occurs entirely due to the hot CNO cycle, and find explosions for a bit lower metallicity.

In the rotating models, the timescale for collapse and bounce phase is reduce because rotating models are more compact and have higher initial central density and temperature.

1) Critical metallicity for explosion in the spherical case: $Z=4\times10^{-3}$

2) Critical metallicity for explosion in the rotating case: $Z=8\times10^{-4}$
Results SMSs collapse to BH
Mass of the AH normalized to the ADM mass

Neutrino luminosity
Conclusions

- Investigating collapse of SMSs and SMBH formation taking into account:
  
  General relativity
  EOS which includes creation of pairs
  H and He burning expected to take place

Determined the critical initial metallicities needed to cause a thermal bounce and for non-rotating and rotating SMSs

We find that these critical metallicities are most probably too high compared to the values that may be present the environment in which this object may form, which favours the picture of SMBH seed formation through the collapse of rotating SMSs

Computed neutrino luminosities, which agree well with those of Linke et al. (2001)