Massive Black Hole Growth and Formation: Implications for LISA

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   - Theoretical Issues
   - Observational Constraints & Clues

2. Does a Galaxy Merger Imply a Black Hole Merger?
   - Where Are the Binaries?
   - Gas-Rich vs. Gas-Poor Mergers

3. What About the LMBH?
   - Do They Exist? Pop. III Seeds

Fan et al. 2003
The existence of massive black holes is not necessarily so surprising. Many roads lead to a massive black hole? (Gravity is one way.)

Rees 1984
Timescale Problem:

\[ L_{acc} = \varepsilon \dot{M}_{BH} c^2 \quad \text{vs.} \]

\[ L_{Edd} = 4\pi G M_{BH} m_p / \sigma_T \]

\[ \rightarrow \text{exponential growth on timescale} \]

\[ t_{\text{Salpeter}} = \frac{\varepsilon \sigma_T c}{4\pi G m_p} \approx 45 \varepsilon_{0.1} 10^6 \text{ yr} \]

\[ t_{\text{Hubble}}(z \leq 6) \leq 10^9 \text{ yr}, \text{i.e., marginally sufficient number of} \]

\[ \text{growth e-foldings possible} \]

\[ \text{(even for } 100 \text{ M}_\odot \text{ seed)} \]

Problem worse if \[ t_{acc} \leq N_{AGN} / N_{Gal} (c / H_o) \leq 10^6 - 10^8 \text{ yr} \]

Need to pack a lot of gas into small region FAST!
Formation of the First Quasars

- Seed BH by direct collapse of primordial gas cloud
  

- Problem:
  - Gas cooling
  - Fragmentation
  - No compact central object!
  - Star Formation
  - Negative Feedback (SNe)

Mass $\sim 10^9 \, M_\odot$, $R \sim 1$ kpc
$z_{\text{vir}} = 5$, no DM
How to make life easier?

Give up Eddington limit? Not so hard… accreting compact objects in our galaxy seem to do it!

Remember Eddington limit only applies to isotropic configurations, while gas flows in strong radiation fields are not. If really throw a lot of gas onto hole, can trap radiation and advect it into hole (e.g., Begelman 1978)

Pre-existing Massive Seeds!

Are they big ($10^6$ solar masses) or small (10-100 solar masses)? When do they appear and how rare are they? Big impact on LISA event rate!
HST QSO hosts

Bahcall et al. 2000
A “boring” object in the sky: the nearby elliptical galaxy M87
Galaxy M84 Nucleus
Hubble Space Telescope • WFPC2 • STIS

PRC97-12 • ST Sci OPO • May 12, 1997 • B. Woodgate (GSFC), G. Bower (NOAO) and NASA
Soltan 1982-type argument/problem:

\[ \rho_{acc} = 1.4 \times 10^5 \left( f_B \varepsilon / 0.01 \right)^{-1} M_\odot \text{Mpc}^{-3} \]

vs.

\[ \rho_{relic\ BH} = 1.1 h \times 10^6 \left( \frac{M_{BH}}{M_{Bu\!l\!g\!e} / \sigma} \right) > / 0.002) (\Omega_{Bu\!l\!g\!e} / 0.002 h^{-1}) M_\odot \text{Mpc}^{-3} \]

\[ \rho_{acc} / \rho_{BH} \ll 1 \Rightarrow \text{accretion irrelevant, mergers key?} \]

most of accretion activity missed, i.e, "dark"

(dust obscuration, low radiative efficiency

accretion solns: super-Eddington photon-trapping,

ADAF, etc.)

(e.g., Natarajan 1999 review)
The X-Ray Background  (mostly AGN, hard X-rays clean BH signal)

Fig. 1. The extragalactic X-ray background spectrum from 0.2 to 400 keV. Different colors correspond to measurements by different missions/instruments as labeled. The reference list for the shown data is the following: ROSAT 0.25 keV (Warwick & Roberts 1998); ROSAT 0.5-2.4 keV (Georgantopoulos et al. 1996); HEAO-1 A2 HED + A4 LED (Gruber 1992; Gruber et al. 1999); HEAO-1 A4 MED (Kinzer et al. 1997); SAX (Vecchi et al. 1999); ASCA SIS (Gendreau et al. 1995); ASCA GIS (Kushino et al. 2002); XMM (Lumb et al. 2002); CDFS (Tozzi et al. 2001a).
The “Unified” AGN Model:

Type I ↔ Type 2

Orientation Effect?

Urry & Padovani 1995
The standard ingredients for an XRB model (e.g., Comastri et al. 1995, Gilli et al. 2002)

Figure 2: Multi wavelength spectrum of a typical Type 1 AGN. From Manners (2002)

Figure 3: Multi wavelength SED of the type 2 AGN NGC 6240 (lines). Blue data points are observed fluxes for a Type II AGN discovered in the CDFS, as reported by Norman et al (2002)

Figure 6: Effects of photoelectric absorption in the soft X-ray region.

"Type II"
Deep ROSAT (one week exposure) of Lockman Hole Region

An image in only the 0.3-2.0 keV energy band  
[Chandra spacecraft can do this in half a day!]

1000-2000+ sources per square degree!
The acid test: what happens when you start adding hard X-rays?
Aside: Chandra < 1” angular resolution absolutely critical! At R=27+ (>40% faint Chandra sources), optical source density is huge … [counterpart confusion serious problem for ROSAT, and even XMM]

Real HST GEMS data, w/real Chandra (1.5”) + simulated XMM (8”) error circles superimposed.
Figure 7: XRB Background spectrum compared to the integrated spectrum of sources obtained by Gilli et al (2001). Model A assumes a constant ratio of Type 2 to Type 1 AGN of 4:1, while in model B this ratio changes with redshift.

Figure 8: Redshift distribution of sources in the Lockman Hole and CDF-N, that resolved $\sim 80\%$ of the XRB on average (histogram) compared to the redshift distribution of sources in the Gilli et al (2001) model (lines).

Hasinger 2003
FIGURE 3. Hardness ratio versus rest frame luminosity in the total 0.5-10 keV band. Objects are coloured according to their X-ray/optical classification: filled black diamonds correspond to type-1 AGN, open red hexagons to type-2 AGN, green triangles to galaxies and blue squares to extended X-ray sources. The large asterisks indicates type-2 QSOs. A critical density universe with $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ has been adopted. Luminosities are not corrected for possible intrinsic absorption.
More narrow line low-power objects at lower z?
If select quasars by non-standard technique, indeed find “weird” objects!

Some show broad optical emission lines but absorbed X-rays??

2MASS Red/NIR Quasar Survey

(very bright, nearby objects; analog of Hellas2XMM)

Fig. 1.— The observed X-ray-to-$K_s$ flux ratio (1 keV X-ray flux assuming a normal AGN X-ray spectrum: $\alpha_E = 1.0, N_H = 3 \times 10^{20} \text{ cm}^{-2}$) as a function of redshift for the 2MASS AGN (circles) compared with the same ratio for low-redshift, broad-line AGN (Elvis et al. 1994; crosses). Upper limits are indicated by triangles and the reddest sources ($J - K_s > 2.5$) by a central dot. The squares show the BAL QSOs IRAS07598+6508 and FIRSTJ0840+3663 (Green et al. 2002, Low et al. 1989, 2MASS survey).
Further complications… confusion w/starburst

Sample of 56,000 emission-line galaxies!

Heckman (+ SDSS) 2003

Fig. 1.2. Diagnostic flux-ratio diagram for a sample of nearly 56,000 emission-line galaxies from the SDSS. According to Kewley et al. (2001) galaxies dominated by an AGN will lie above and to the right of the dotted line. Galaxies lying below and to the left of the dashed line are dominated by star-forming regions. Galaxies lying between the dashed and dotted curves are transition objects (AGN and star formation are both important). The locations of classic AGN-dominated Seyfert nuclei and LINERs are indicated.
IR Detection of AGN?

Figure 1  The luminosity function for infrared galaxies compared with other extragalactic objects. References: IRAS RBGS (Sanders et al. 1996a), IRAS 1-Jy Survey of ULIGs (Kim 1995), Palomar-Green QSOs (Schmidt & Green 1983), Markarian starbursts and Seyfert galaxies (Huchra 1977), and normal galaxies (Schecter 1976). Determination of the bolometric luminosity for the optically selected samples was as described in Soifer et al. (1985), except for the adoption of a more accurate bolometric correction for QSOs of $11.8 \times L_{\odot}$ (0.43 mm) (Elvis et al. 1994).

Ready for SIRTF!
In general, nice ROSAT era correlations kaput ...
Thus the density estimates (10) and (11) become

\[ \rho_{\bullet}(z = 0) = (2.5 \pm 0.4) \times 10^5 \, \text{M}_\odot \, \text{Mpc}^{-3}, \]  

(mass-velocity dispersion) \hspace{1cm} (13)

and

\[ \rho_{\bullet,L}(z = 0) = 5.8 \times 10^5 \, \text{M}_\odot \, \text{Mpc}^{-3}. \]  

(mass-bulge luminosity dispersion) \hspace{1cm} (14)

The error estimate in equation (13) represents the combination of the \( \sim 10\% \) uncertainty in the correction factor 1.1 due to intrinsic scatter, and the error estimate in equation (10). The error in equation (14) is difficult to estimate but is certainly much larger than the error in equation (13). Earlier estimates include \( \rho_{\bullet,L}(z = 0) = 3.5 \times 10^7 \, \text{M}_\odot \, \text{Mpc}^{-3} \) (Salucci et al. 1999), \( \rho_{\bullet,L}(z = 0) = 3.7 \times 10^5 \, \text{M}_\odot \, \text{Mpc}^{-3} \) (Merritt & Ferrarese 2001b), and \( \rho_{\bullet,L}(z = 0) = (4 \pm 2) \times 10^5 \, \text{M}_\odot \, \text{Mpc}^{-3} \) (Marconi & Salvati 2001).

VS.

About 56\% of the present density \( \rho_{\text{acc}}^{\text{QSO}}(z = 0) \) is accreted when \( z < 2 \) and 90\% when \( z < 3 \), consistent with our claim that \( \rho_{\text{acc}}^{\text{QSO}}(z = 0) \) is insensitive to uncertainties in the QSO luminosity function at high redshift. The accreted BH mass density during optically bright QSO phases is found to be

\[ \rho_{\text{acc}}^{\text{QSO}}(z = 0) = 2.1 \times 10^5 (\frac{C_B}{11.8})[0.1(1 - \epsilon)/\epsilon] \, \text{M}_\odot \, \text{Mpc}^{-3}, \] (23)

which is independent of the Hubble constant and remarkably close to the value obtained by Chokshi & Turner (1992) using similar methods, \( \rho_{\text{acc}}^{\text{QSO}}(z = 0) = 2.2 \times 10^5 (\frac{C_B}{16.5})(0.1/\epsilon) \, \text{M}_\odot \, \text{Mpc}^{-3} \). If the QSOs have a mass-to-energy conversion efficiency \( \epsilon \approx 0.1 \), \( \rho_{\text{acc}}^{\text{QSO}}(z = 0) \) would be close to the local BH mass density \( \rho_{\bullet} \) (eq. 13), which implies that the local BH mass density comes mainly from accretion during optically bright QSO phases.

The accreted BH mass density can also be inferred from the X-ray and infrared backgrounds, for example, \( \rho_{\bullet}^{\text{X}} \approx (6-9) \times 10^5 (0.1/\epsilon) \, \text{M}_\odot \, \text{Mpc}^{-3} \) in Fabian & Iwasawa (1999), \( \rho_{\bullet}^{\text{IR}} \approx (7.5-16.8) \times 10^5 (0.1/\epsilon) \, \text{M}_\odot \, \text{Mpc}^{-3} \) in Elvis, Risaliti & Zamorani (2002), \( \rho_{\bullet}^{\text{IR}} \approx 7.5 \times 10^5 (0.1/\epsilon) \, \text{M}_\odot \, \text{Mpc}^{-3} \) in Haehnelt & Kauffmann (2001). Multi-waveband (including optical and far infrared) observations of Chandra hard X-ray sources give \( \rho_{\bullet}^{\text{H}X+\text{OPT}+\text{FIR}} \approx 9 \times 10^5 (0.1/\epsilon) \, \text{M}_\odot \, \text{Mpc}^{-3} \) in Barger et al. (2001).

Fabian & Iwasawa (1999) conclude that 85\% of the emitted energy from AGNs has been absorbed, so that a large fraction of the local BH mass density must be due to obscured QSOs, which do not contribute to the estimate in equation (23). Thus, their estimate \( \rho_{\bullet}^{\text{X}} \) exceeds \( \rho_{\text{acc}}^{\text{QSO}}(z = 0) \) by a factor 3–4, and then the comparison of \( \rho_{\bullet}^{\text{X}} \) with the local BH mass density (eq. 13) implies the efficiency \( \epsilon \sim 0.3-0.5 \), at or beyond the upper limit of plausible accretion processes, \( \epsilon = 0.31 \) (Thorne 1974). Elvis,
Observational Debates & Clues

Rare long-lived AGN vs. many short-lived AGN?
Seems to be tilting decisively towards

\[ M - \sigma \text{ relation,} \]

\[ (\Rightarrow \text{many relic SMBH}) \]

X-ray/2MASS counts

\[ (\Rightarrow \text{many active AGN missed optically}) \]

No more Soltan/\( M - \sigma \) problem?

Also, \( M - \sigma \) relation \( \Rightarrow \) BH and galaxy know about each other!?
Galaxy & BH formation same process?
(Once correct for obscuration, redshift evolution similar?)

Mergers/gas are clearly important in at least AGN phase.
Where are the SMBH binaries?

3C 75: Merger Starting?
“Smoking Gun?”

NGC 326

Ekers & Merrit, 2002
NGC 6240: current best case for an eventual merger?

Figure 3: This composite view shows (upper left) a Hubble Space Telescope optical picture of the "cosmic train wreck" NGC 6240, two gas-rich galaxies that have collided and are in the process of merging, and (lower right) a Chandra X-ray image of the central parts of this system. At the highest X-ray energies (shown in the image by the color blue) the hot gas of the galaxy and its stars disappear from view and only two bright point sources remain: two quasar nuclei powered by supermassive black holes. These black holes are separated by only 4000 light years and likely have been caught in the process of inspiraling and merging in the manner described here.

Simulation of idealized gas-rich merger...

Dynamical friction phase

A. Escala 2003
What happens when a binary forms?

Drag continues!

(If there’s enough gas...)
Merger happens very fast!
Strain Amplitudes During Last Year Before BH-BH Coalescence

BH-MBH Binaries at z=3
- 1 yr before coalescence
- 0.1 yr before coalescence
- just before coalescence

Log Gravitational Wave Amplitude $h$

$10^6/10^8 M_e$
$10^5/10^7 M_e$
$10^4/10^6 M_e$
$10^3/10^5 M_e$
$10^2/10^4 M_e$

Binary Confusion Noise Threshold Estimate

LISA Instrumental Threshold
5 million km arms
1 yr integration, S/N=5

Bender and Pollack 2003
Black holes in globular clusters?

One of best studied cases: M15

a 2000 solar mass black hole?

Guhathakurta et al. 1996

Gebhardt et al. 2000
ULXs and IMBHs

M82
Fabbiano et al. 2001, CXO
Region of Primordial Star Formation

- Gravitational Evolution of DM
- Gas Microphysic:
  - Can gas sufficiently cool?
  - $t_{\text{cool}} < t_{\text{ff}}$ (Rees-Ostriker)

- Collapse of First Luminous Objects expected:
  - at: $z_{\text{coll}} = 20 - 30$
  - with total mass: $M \sim 10^6 M_\odot$
How massive were the First Stars?

Previous estimates: $1 \, M_\odot < M_{\text{PopIII}} < 10^6 \, M_\odot$

Massive Black Hole

Cluster of Stars

$M \sim 10^6 \, M_\odot$

normal IMF

Top-heavy IMF
The Physics of Population III

- **Simplified physics**
  - No magnetic fields yet (?)
  - No metals → no dust
  - Initial conditions given by CDM
    → Well-posed problem

- **Problem:**
  How to cool primordial gas?
  - No metals → different cooling
  - Below $10^4$ K, main coolant is $H_2$

- $H_2$ chemistry
  - Cooling sensitive to $H_2$ abundance
  - $H_2$ formed in non-equilibrium
    → Have to solve coupled set of rate equations
Cosmological Initial Conditions

- Consider situation at $z = 20$

Gas density

~ 7 kpc

Primordial Object
The First Star-Forming Region

$M \sim 10^6 M_\odot$

1 kpc

$\sim 7$ kpc
Formation of a Population III Star

\[ M_{\text{halo}} \sim 10^6 M_\odot \]

\[ M_{\text{clump}} \sim 10^3 M_\odot \]

\( 1 \text{ kpc} \)  
(see also Bromm, Coppi, & Larson 1999, 2002)

\( \sim 25 \text{ pc} \)
A Physical Explanation:

- Gravitational instability (Jeans 1902)
  - Jeans mass: $M_J \sim T^{1.5} n^{-0.5}$

- Thermodynamics of primordial gas

Two characteristic numbers in microphysics of H$_2$ cooling:
- $T_{\text{min}} \sim 200$ K
- $n_{\text{crit}} \sim 10^3 - 10^4$ cm$^{-3}$ (NLTE → LTE)

- Corresponding Jeans mass: $M_J \sim 10^3 M_\odot$
The Crucial Role of Accretion

- Final mass depends on accretion from dust-free Envelope
- Development of core-envelope structure
  - Omukai & Nishi 1998, Ripamonti et al. 2002
- $M_{\text{core}} \sim 10^{-3} M_\odot$ → very similar to Pop. I
- Accretion onto core → very different!
- $\frac{dM}{dt}_{\text{acc}} \sim \frac{M_J}{t_{\text{ff}}} \sim T^{3/2}$ (Pop I: $T \sim 10$ K, Pop III: $T \sim 300$ K)
- Can the accretion be shut off in the absence of dust?
Protostellar Collapse
(Bromm & Loeb 2003, astro-ph/0301406)

- Simulate further fate of the clump
The Crucial Role of Accretion

\[ \frac{dM}{dt} \propto t^{-0.55} \]

\[ M_* \propto t^{0.45} \]

\[ M_* (t = 3 \times 10^6 \text{ yr}) \approx 700 M \]
The Death of the First Stars:
(Heger et al. 2002)
What happens to pop III remnant BH? Madau et al. 2003?

Fig. 1.— Fraction of BH host halos that contains two or more seed IMBHs as a function of redshift, averaged over 50 `trees'. Two curves are shown, one assuming BHs form in isolation within mini-

Fig. 3.— Mass function of accreting IMBHs predicted at four different redshifts by our fiducial model. Units are arbitrary. All seed holes are assumed to form at $z = 24$ from $3.5\sigma$ density peaks.

Fig. 6.— Contribution of nuclear, wandering, and intergalactic holes to the IMBH mass density as a function of redshift. In each major merger a mass $\Delta m_{acc} = 10^{-5} M_\odot$ is accreted onto the BH in the main halo. Left panel: model in which (most) binaries stall. Right panel: model in which binaries shrink rapidly. Solid line: mass density of IMBHs in galaxy nuclei. Long-dashed line: wandering IMBHs retained in galaxy halos, mostly due to minor mergers. Short-dashed line: intergalactic IMBHs ejected from the host after a gravitational rocket. The horizontal dotted line shows the mass density of SMBHs in the nuclei of nearby galaxies inferred by Yu & Tremaine (2002).
First Dwarf Galaxies as Sites of BH Formation
(Bromm & Loeb 2003)

- 2 sigma peak
- $M \sim 10^8 M_0$, $z_{\text{vir}} \sim 10$
- $T_{\text{vir}} \sim 10^4$ K
  → Cooling possible due to atomic H

- Suppress star formation:
  - Photo-dissociation of $H_2$:
    
    \[ H_2 + h\nu \rightarrow 2H \]
  - Lyman – Werner photons:
    \[ h\nu = 11.2 – 13.6 \text{ eV} \]
En Route to a Supermassive Black Hole?

- Consider gas distribution in central 100 pc

Low-spin

High-spin

Single object: $M \sim 10^6 M_\odot$

Binary: $M_{1,2} \sim 10^6 M_\odot$
Summary:

SMBH growth must be a rapid and relatively robust process. Can happen very early on. Probably intimately tied to galaxy merger induced activity, especially nuclear star formation (M-σ relation!).

Observations of SMBH improving rapidly. Field in state of flux. Chandra + SIRTF especially powerful, overcome obscuration problem to uncover true AGN and star formation activity.

SMBH growth by merger vs. accretion? Both? 😊 Today, looks like accretion may be dominant mode.

SMBH growth greatly facilitated by pre-existing massive “seeds.” Nature of number of seeds is major uncertainty in expected LISA event rate.

Primordial (Pop. III) seeds appear plausible => very high z mini-AGN, WMAP reionization? Mergers and GRBs? High overall LISA rate? Especially if M-σ relation holds for early AGN, LISA powerful probe of early structure formation, at z > 10!?
Would be reassuring to actually find some MBH binaries before LISA. Where are they? Maybe binaries don’t accrete efficiently? NGC 6240 currently best and perhaps cautionary example. Binary BH merge quickly and are obscured? If so, EM counterpart to LISA signal may be difficult to find? Angular resolution key to finding correct counterpart.

Would also be nice to find IMBH/LMBH. Evidence scant right now. IMHO, most ULXs are NOT IMBH but beamed/super-Eddington stellar mass objects (e.g., GRS 1915 in our galaxy). However, a few ULXs are best explained as massive objects and there are a couple known AGN with $M \leq 10^5 \, M_\odot$.

Large characteristic Jeans mass for fragmentation might actually occur today, e.g., in galactic nuclei. Strong ionizing radiation field (e.g., from AGN) wipes out metal coolants, heats gas? Top heavy IMF? Most massive stars in our galaxy near galactic center. More massive remnants + dissipative central gas => good for LISA!

Effects of BH spin seems to be major LISA signal uncertainty. If MBH grow by accretion, easy to get maximally rotating hole. Don’t ignore!?
Metal abundance higher than solar, everything happens fast

Abandon eddington limit

Seed

Small or not? Blob vs. hierarchical formation?

Tightness of M-sigma?
Easy to understand scaling
Why the constant, i.e., why scatter so small?
Seeds!!!

Lesson from present day star formation

Bender “LMBH”
The Diffuse Extragalactic Background

Fig. 1.—The background radiation spectrum of the universe: (1) radio, (2) cosmic microwave background, (3) FIRAS excess (Fixen et al. 1998), (4) DIRBE background (points with error bars) and DIRBE upper limits (Hauser et al. 1998), (5) optical background (Hernstein 1998), (6) ultraviolet background (Murthy et al. 1999; Henry & Murthy 1994; Henry 1991), (7) the interstellar medium photoionization optical depth (right-hand scale) for 10⁵, 10⁶, and 10⁷ H atoms cm⁻², (8) soft X-ray background, and (9) high-energy background. In this diagram, an equal plotted value means an equal amount of energy per logarithmic interval of frequency. The new Fixen et al. upper limit between 912 and 1216 Å of Murthy et al. (1999) suggests that the transition from the high background in the visible to the low background in the X-ray may occur at 1216 Å, which in turn would suggest that the ultraviolet and visible background at high galactic latitudes is redshifted Lyα recombination radiation.
From the Dark Ages to the Cosmic Renaissance

FROM THE DARK AGES...
After the emission of the cosmic microwave background radiation (about 400,000 years after the big bang), the universe grew increasingly cold and dark. But cosmic structure gradually evolved from the density fluctuations left over from the big bang.

...TO THE RENAISSANCE
The appearance of the first stars and protogalaxies (perhaps as early as 100 million years after the big bang) set off a chain of events that transformed the universe.

- First Stars → Transition from Simplicity to Complexity
Fig. 1.— Redshift (solid for spectroscopic, open for photometric) vs. 2–8 keV flux for the X-ray samples (squares—CDF-N; triangles—A370, SSA13, and SSA22; diamonds—LH-NW; circles—ASCA). Broad-line optical spectra are denoted by large solid symbols. Unidentified sources are denoted by small solid symbols at z < 0. Solid curves show flux vs. redshift for $L_x = 10^{42}$ ergs s$^{-1}$ (lowest curve), $10^{43}$, $10^{44}$, and $10^{45}$ (highest curve), computed with a K-correction for a $\Gamma = 1.8$ power law spectrum (see Barger et al. 2002).
Paradise Lost: The Transition to Population II

- Add trace amount of metals
- Limiting case of no H$_2$
- Heating by photoelectric effect on dust grains

Consider two identical (other than Z) simulations!
Effect of Metallicity:

$Z = 10^{-4} Z_\odot$  
$Z = 10^{-3} Z_\odot$

- Insufficient cooling
- Vigorous fragmentation

→ Critical metallicity: $Z_{\text{crit}} \sim 5 \times 10^{-4} Z_\odot$
The First Supernova-Explosion

Gas density

- $E_{SN} \sim 10^{53}$ ergs
- Complete Disruption (PISN)

$\sim 1$ kpc
Fig. 4.—(a) Number density of sources with rest-frame 2–8 keV luminosities between \(10^{43}\) and \(10^{44}\) erg s\(^{-1}\) (solid symbols) and between \(10^{44}\) and \(10^{45}\) erg s\(^{-1}\) (open symbols) versus redshift. Diamond is from this paper, and circles are from Cowie et al. (2002b). Points below (above) \(z = 2\) were determined from the observed-frame 2–8 keV (0.5–2 keV) sample. An intrinsic \(\Gamma = 1.8\) was assumed, for which there is only a small differential \(K\)-correction to correct to rest-frame 2–8 keV. Poissonian 1\(\sigma\) uncertainties are based on the number of sources in each redshift interval. Horizontal bars show the maximal LF in the \(10^{43}\) to \(10^{44}\) erg s\(^{-1}\) range found by assigning all the sources that could lie in each redshift (and then luminosity) interval a redshift at the center of the interval. (b) As in (a) but for an \(\Omega_M = 1, \Omega_{\Lambda} = 0\) cosmology with \(H_0 = 50\) km s\(^{-1}\) Mpc\(^{-1}\). Dot-dashed curves show the 2dF quasar LF of Boyle et al. (2000): upper curve is for objects with absolute 1450 Å magnitudes brighter than \(-23\) (quasars) that roughly matches our \(L_x > 10^{44}\) erg s\(^{-1}\) selection, lower curve is for objects brighter than \(-26.8\) that matches the SDSS sensitivity to high-redshift quasars. Dashed line shows the SDSS objects brighter than \(-26.8\) in the \(z = 3.5\) to \(z = 6\) range. Solid square and uncertainty is for the SDSS \(z > 5.7\) quasar sample to \(-26.8\) (Fan et al. 2001b).
Region of Primordial Star Formation

- Gravitational Evolution of DM
- Gas Microphysic:
  - Can gas sufficiently cool?
  - $t_{\text{cool}} < t_{\text{ff}}$ (Rees-Ostriker)
- Collapse of First Luminous Objects expected:
  - at: $z_{\text{coll}} = 20 - 30$
  - with total mass: $M \sim 10^6 M_\odot$
A Tale of Two Timescales

- Consider the cooling and freefall times:

  Timescale vs. $n$

- Gas particles loiter at: $n \sim 10^3 - 10^4$ cm$^{-3}$
  - $t_{\text{cool}} \sim t_{\text{ff}}$
  - Quasi-hydrostatic phase
- Runaway collapse occurs
  - s.t. $t_{\text{cool}} \sim t_{\text{ff}}$
The First Supernova Explosions
(with N. Yoshida & L. Hernquist)

\[ M \sim 10^6 \, M_\odot \]

1 kpc

\sim 7 \, \text{kpc}
HII Regions around the First Stars

1 kpc
Simulating the Formation of the First Stars:  
(Bromm, Coppi, & Larson and Bromm & Hernquist)

- Use TREESPH / Gadget (both DM and gas)
- Radiative cooling of primordial gas
- Non-equilibrium chemistry
- Initial conditions: ΛCDM
- Modifications to SPH:
  - sink particles
  - particle splitting
Thermodynamics and Structure

$T$ vs. $\log n$

Phase Distribution
Dense-shell Formation

Timescale vs Radius

- $t_{cool}$
- $t_{ff}$
- $t_{shock}$

Inverse Compton cooling
The First Supernova-Explosion

Gas density

- $\sim 1 \text{kpc}$
- $E_{SN} \sim 10^{53} \text{ergs}$
- Complete Disruption (PISN)
Nucleosynthetic Evidence:
(Qian & Wasserburg 2002)

- Signature of VMS enrichment at $[\text{Fe/H}] < -3$
- Normal (Type II) SNe at higher $[\text{Fe/H}]$

Heavy r-process abund. vs. $[\text{Fe/H}]$
Cosmic Star Formation History
(Mackey, Bromm & Hernquist 2003)

- 2 modes of SF:
  - Pop III → VMS
  - Pop I / II → normal stars

- Pop III SF possible in halos with:
  - $T_{\text{vir}} < 10^4 \text{K} \rightarrow$ molecular cooling
  - $T_{\text{vir}} > 10^4 \text{K} \rightarrow$ atomic H cooling

Comoving SFR vs. redshift

(Springel & Hernquist 2003)
Cosmic Star Formation History
(Mackey, Bromm & Hernquist 2003)

Comoving SFR vs. redshift

- Dominant Pop III SF expected in halos with: $T_{\text{vir}} > 10^4 K \rightarrow$ atomic H cooling
- Strong negative feedback suppresses SF in mini-halos (radiative and mechanical)
The Pop III → Pop II Transition
(Mackey, Bromm & Hernquist 2003)

Metallicity SFR vs. redshift

$Z_{\text{crit}}$ 50%

$Z_{\text{crit}}$ 5%

$Z_{\text{tran}} \sim 15 - 20$
Relic of the Dawn of Time:

- HE0107-5240: $[\text{Fe/H}] = -5.3$ (Christlieb et al. 2002)

What does this star tell us about Population III?
Metal Poor Halo Stars and the First Stars:
(with Schneider, Ferrara, Salvaterra, & Omukai 2003, Nature in press)

- Abundance pattern:
  - core-collapse SN
  - PISN

- Break degeneracy:
  - r-process elements

- $Z < Z_{\text{crit}}$?
  - role of dust
  - shock-compression
  - statistics

<table>
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<th>Element/Fe</th>
<th>Li</th>
<th>C</th>
<th>N</th>
<th>Na</th>
<th>Mg</th>
<th>Ca</th>
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First Dwarf Galaxies as Sites of BH Formation

- 2 sigma peak
- $M \sim 10^8 \, M_0$, $z_{\text{vir}} \sim 10$
- $T_{\text{vir}} \sim 10^4 \, \text{K}$
  → Cooling possible due to atomic H

- Suppress star formation:
  - Photo-dissociation of $\text{H}_2$:
    \[
    \text{H}_2 + h \, \nu \rightarrow 2 \, \text{H}
    \]
  - Lyman – Werner photons:
    \[
    h \, \nu = 11.2 – 13.6 \, \text{eV}
    \]
Gamma-Ray Bursts as Probes of the First Stars:

- GRB progenitors → massive stars
- GRBs expected to trace cosmic SFH
- Swift mission:
  - Launch in 2003
  - Sensitivity → GRBs from $z > 15$
Expected Redshift Distribution of GRBs:

SF History

GRB Redshift Distribution

- Fraction of all burst from \( z > 5 \): \( \sim 50\% \)
- Fraction of GRBs detected by \textit{Swift} from \( z > 5 \): \( \sim 25\% \)

Summary

- Primordial gas typically attains:
  - $T \sim 200 - 300 \text{ K}$
  - $n \sim 10^3 - 10^4 \text{ cm}^{-3}$
- Corresponding Jeans mass: $M_J \sim 10^3 \text{ M}_\odot$
- Pop III SF might have favored very massive stars
- Transition to Pop II driven by presence of metals ($z_{\text{trans}} \sim 15 - 20$)
- PISNe completely disrupt mini-halos and enriches surroundings
- Metal-poor halo stars as probes of the first stars
Perspectives:

- Further fate of clumps
  - Feedback of protostar on its envelope
  - Inclusion of opacity effects (radiative transfer)

- The "Second Generation of Stars"

- SN feedback and metal enrichment from the first stars

- How does a VMO evolve and die?

- Observability (lensing?) and statistics of high-z SNe
132 node Beowulf cluster (AMD Athlon)
The Mass of a Population III Star

- Central core in free-fall: $M \sim 100 \, M_\odot$
- Extended envelope with isothermal density profile

$\Rightarrow$ First stars were predominantly very massive
Implications of a Heavy IMF For the First Stars

• Consider: $100 \, M_\odot < M < 1000 \, M_\odot$ (VMO)

• Structure determined by:
  - Radiation pressure, Luminosity close to EDDINGTON limit

$log L$ vs. $log T_{\text{eff}}$

• For Pop III:
  $T_{\text{eff}} \approx 110,000 \, K$
  $\rightarrow$ lambda peak $\approx 250 \, \AA$

  (close to He II ionization edge)
How Do VMOs Evolve?

- Nuclear burning up
- He ignition
- Estimated lifetime: $3 \times 10^6$ yr
- Crucial uncertainty: Mass loss ???

$\log L$ vs. $\log T_{\text{eff}}$

![Graph showing log L vs. log T eff with labeled points and lines indicating different stages of stellar evolution.](image)
Spectral Signature

Flux vs. Wavelength

- Strong NLTE effects
- Close to black-body form
- Lines of H I and He II
A Generic Spectrum

$L_{\nu}/M$ vs. $\lambda$

- Spectra very similar for $M > 300 \ M_\odot$
- Predict composite spectrum almost *independent* of IMF

- Ionizing photon production
- Rare 3 sigma peaks may suffice to reionize the Universe

<table>
<thead>
<tr>
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<th>$E$ [eV]</th>
<th>$Y$</th>
<th>$f_*$</th>
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<td>H I</td>
<td>13.6</td>
<td>~ 16</td>
<td>$1 \times 10^{-4}$</td>
</tr>
<tr>
<td>He I</td>
<td>24.6</td>
<td>~ 14</td>
<td>$1 \times 10^{-5}$</td>
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<tr>
<td>He II</td>
<td>54.4</td>
<td>~ 75</td>
<td>$4 \times 10^{-5}$</td>
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Probing the Primordial IMF with NGST

- Observed spectrum: Heavy IMF vs. Salpeter IMF

Observed flux vs. Wavelength

- Salpeter case from Tumlinson & Shull 2000

• Observed spectrum from cluster with heavy IMF is significantly bluer
Why Study Population III?

• The Quest for our Origins
• Importance for Cosmological Structure Formation
  • Reheat / Reionize the Universe
    ➔ Feedback effects on IGM
  • Initial enrichment with metals
    ➔ Pure H/He out of BBNS
    ➔ Need stars to synthesize heavy elements
  • Pop III remnants
    ➔ Baryonic DM (?)

• Upcoming Observations
  • CMB anisotropy probes (WMAP / Planck)
    ➔ Study imprint of first stars
  • IR missions (SIRTF/ JWST)
    ➔ Direct imaging
The Crucial Role of Accretion

\[ \frac{dM}{dt} \propto t^{-0.55} \]

\[ M_\ast \propto t^{0.45} \]
Fig. 2. Soft (left) and hard (right) logN-logS compared with the predictions of model B by GSH01. Different curves correspond to the contribution of different classes of objects as labeled. The galaxy counts predicted by the Ranalli et al. (2002) model are also plotted as a dotted line. CDFS and CDFN data are from Rosati et al. (2002) and from Brandt et al. (2001). The CDFN fluctuation analysis box is adapted from Miyaji & Griffiths (2002). ROSAT data are from Miyaji et al. (2000). ASCA data (black squares) at $f_{2-10} = 4 \times 10^{-14}, 7 \times 10^{-14}$ and $> 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ are from Ogasaka et al. (1998), Ueda (2001) and Cagnoni et al. (1998), respectively. The deepest datapoint in the hard logN-logS is from Moretti et al. (2002).