Introduction to Dark Stars

Dark Stars are stars made of ordinary matter that shine thanks to the annihilation of dark matter.

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The original Pop III Dark Stars

The first stars to form in the universe may have been powered by dark matter annihilation instead of nuclear fusion.

They were *dark-matter powered stars* or for short *Dark Stars*

- Explain chemical elements in old halo stars
- Explain origin of supermassive black holes in early quasars

*Spolyar, Freese, Gondolo 2008*
*Freese, Gondolo, Sellwood, Spolyar 2008*
*Freese, Spolyar, Aguirre 2008*
*Freese, Bodenheimer, Spolyar, Gondolo 2008*
*Natarajan, Tan, O’Shea 2009*
*Spolyar, Bodenheimer, Freese, Gondolo 2009*
**Dark Matter Burners: Dark Stars**

Stars living in a dense WIMP environment may gather enough WIMPs and become Dark Stars.

- Explain young stars at galactic center?
- Prolong the life of Pop III Dark Stars?

**References:**
- Salati, Silk 1989
- Moskalenko, Wai 2006
- Fairbairn, Scott, Edsjo 2007
- Spolyar, Freese, Aguirre 2008
- Iocco 2008
- Bertone, Fairbairn 2008
- Yoon, Iocco, Akiyama 2008
- Taoso et al 2008
- Iocco et al 2008
- Casanellas, Lopes 2009

*Galactic center example courtesy of Scott*
How do WIMPs get into stars?

Some stars are born with WIMPs

First stars (Pop III)
Sun

Some stars capture them later

Stars living in dense dark matter clouds (main sequence stars, white dwarfs, neutron stars, Pop III stars)
What do WIMPs do to stars?

“If heavy neutrinos exist, they would substantially affect stellar evolution. They could [...] provide an additional source of luminosity through annihilation, and increase the rate of energy transport.”

Steigman, Sarazin, Quintana, Faulkner 1978
What do WIMPs do to stars?

Provide an extra energy source

Gravitational systems like stars have negative heat capacity. Adding energy makes them bigger and cooler.

May provide a new way to transport energy

Ordinary stars transport energy outward by radiation and/or convection. WIMPs with long mean free paths provides additional heat transport.

May produce a convective core (or become fully convective)

Very compact WIMP distributions generate steep temperature gradients that cannot be maintained by radiative transport.
The Hertzsprung-Russell diagram
Formation of ordinary stars

Hayashi track

Hayashi forbidden region
Two ways of gathering dark matter

- **By gravitational contraction:** when object forms, dark matter is dragged in into deeper and deeper potential
  - adiabatic contraction of galactic halos due to baryons (Zeldovich et al 1980, Blumenthal et al 1986)
  - dark matter concentrations around black holes (Gondolo & Silk 1999)
  - dark matter contraction during formation of first stars (Spolyar, Freese, Gondolo 2007)

- **By capture through collisions:** dark matter scatters elastically off baryons and is eventually trapped
  - Sun and Earth, leading to indirect detection via neutrinos (Press & Spergel 1985, Freese 1986)
  - stars embedded in dense dark matter regions (“DM burners” of Moskalenko & Wai 2006, Fairbairn, Scott, Edsjo 2007-09)
  - dark matter in late stages of first stars (Freese, Spolyar, Aguirre; Iocco; Taoso et al 2008; Iocco et al 2009)
In equilibrium, the annihilation rate equals the capture rate, so the total WIMP luminosity equals mass x capture rate.

Previous use of WIMP capture rates

Dark matter particles sink into the Sun where they transform into neutrinos.

High-energy neutrinos from the Sun.
The main sequence shifts to lower temperatures and higher luminosities

Salati, Silk 1989

Ambient DM density \( \rho \leq 4 \times 10^7 \text{ GeV/cm}^3 \)

\( \sigma = 4 \times 10^{-36} \text{ cm}^2 \)

\( v = 300 \text{ km/s} \)

\( 1 \text{ } M_\odot/\text{pc}^3 = 38 \text{ GeV/cm}^3 \)
Dark Stars by capture

Main sequence star inside a WIMP cloud

Geneva evolution code

\( \sigma_{SD} = 10^{-38} \text{ cm}^2 \)

\( v = 10 \text{ km/s} \)

\( 10^8 \text{ GeV/cm}^3 < \rho < 10^{11} \text{ GeV/cm}^3 \)

Lifetime longer than age of Universe for \( \rho \approx 5 \times 10^{10} \text{ GeV/cm}^3 \)

Taoso, Bertone, Meynet, Ekstrom 2008
Dark Stars by capture

Zero metallicity star at redshift $z \approx 20$

$\sigma_{SD} = 10^{-38}$ cm$^2$

$v = 10$ km/s

$10^8$ GeV/cm$^3 < \rho < 10^{12}$ GeV/cm$^3$

 Modified Padova stellar code
Figure 4. Evolutionary tracks followed in the HR diagram by stars of various masses, when WIMPs provide different fractions of their total energy budgets.

Filled, unlabelled circles indicate the starting points of tracks, whilst labelled ones give indicative ages during the evolution of $1.4 M_\odot$ stars. Tracks have been halted when the star exhausts the supply of hydrogen in its core or reaches the current age of the Universe. Stars with a greater luminosity contribution from WIMPs push further up the Hayashi track and spend longer there before returning to the main sequence. Stars which come to be entirely dominated by WIMP annihilation (bottom right-hand panel) evolve quickly back up the Hayashi track and halt, holding their position in the HR diagram well beyond the age of the Universe.

In Figs 4 and 5 we show evolutionary tracks in the HR and central equation-of-state diagrams of stars with different masses and WIMP luminosities. At low WIMP luminosities, the evolution is essentially normal. As WIMPs are allowed to provide more energy, the negative heat capacity of a star causes it to expand and cool. The central temperature and density drop, nuclear burning reduces and the star moves some distance back up the Hayashi track. The reduction in central temperatures and overall luminosities provided by pp-chain and CNO-process hydrogen burning are illustrated in Fig. 6. These values are taken at the time $t_{\text{adjust}}$ when a star has completed its initial reaction to the presence of WIMPs, which corresponds to the central temperature and density reaching their minima and the star arriving at the bottom leftmost point of its travels in Fig. 5. At very high WIMP luminosities, the stellar core expands and cools drastically, moving stars a long way back along the pre-main sequence and effectively shutting down nuclear burning altogether. Such an object becomes a fully fledged dark star, powered entirely and perpetually by WIMP annihilation.

At intermediate WIMP luminosities, nuclear burning is suppressed rather than completely extinguished. Its continued contribution to nuclear processing slowly raises the core temperature and density once more, in turn increasing the rate of nuclear reactions and accelerating the process. The star burns hydrogen alongside WIMPs, and goes on to evolve through a hybrid WIMP-hydrogen main sequence. Such evolution can be best seen in the bottom left-hand panel of Fig. 4. Thanks to the energy input from WIMP annihilation, the time it takes such a star to consume its core hydrogen is lengthened, so its effective main-sequence lifetime is extended (Fig. 7). The increase in main-sequence lifetime is notable at all metallicities, but most prominent at low $Z$, essentially because normal main-sequence lifetimes are shorter at lower metallicity. We did not see changes with metallicity in the central temperatures, pp-chain or CNO luminosities of the stars in our grid.

We should point out here that in the extreme case of a very large WIMP luminosity, it is highly questionable whether a star can even form.
Dark Stars by contraction

Population III stars

Afterglow Light Pattern 380,000 yrs. Dark Ages Development of Galaxies, Planets, etc.

Inflation

Quantum Fluctuations

1st Stars about 400 million yrs.

Big Bang Expansion 13.7 billion years

Monday, November 9, 2009
Dark Stars by contraction

First Stars: Standard Picture

• Formation Basics
  - first luminous objects ever
  - made only of H/He
  - form inside DM halos of $10^5$-$10^6 \, M_\odot$
  - at redshift $z=10$-$50$
  - baryons initially only 15%
  - formation is a gentle process

• Dominant cooling mechanism to allow collapse into star is $H_2$ cooling (Hollenbach & McKee 1979)
Dark Stars by contraction

First Stars: Standard Picture

Thermal evolution of Pop III protostar

Must be cool to contract

- H₂ formation line cooling (NLTE)
- 3-body reaction
- Collision induced emission
- Opaque to continuum
- Heat release
- Opaque to molecular line
- Loitering (~LTE)
- Adiabatic contraction

Courtesy of N. Yoshida
Dark Stars by contraction

First Stars: Adiabatic Contraction of Dark Matter

(a) using prescription from Blumenthal, Faber, Flores & Primack 1986 (circular orbits only)
   Spolyar, Freese, Gondolo 2008

\[ r M(r) = \text{constant} \]

(b) using full phase-space a la Young 1991
   Freese, Gondolo, Sellwood, Spolyar 2009

(c) using cosmo-hydrodynamical simulations
   Natarajan, Tan, O’Shea 2009
Dark Stars by contraction

First Stars: Adiabatic Contraction of Dark Matter

Figure 2.
First Stars: Three Conditions for a Dark Star

(1) Sufficiently high dark matter density to get large annihilation rate

(2) Annihilation products get stuck in star

(3) Dark matter heating beats $\text{H}_2$ cooling

Leads to new stellar phase
**Dark Stars by contraction**

*First Stars: Birth of a Dark Star*

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**Thermal evolution of Pop III protostar**

Must be cool to contract

\[ m = 100 \text{ GeV} \]

\[ \langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3/\text{s} \]
Dark Stars by contraction

*First Stars: Birth of a Dark Star*

- Dark Star supported by DM annihilation rather than fusion
- DM is less than 2% of the mass of the star but provides the heat source (The Power of Darkness)

*Freese, Bodenheimer, Spolyar, Gondolo 2008*
Dark Stars by contraction

First Stars: Life of a Dark Star

Sequence of polytropes with mass and dark matter accretion

Dark Star phase ends onto Zero Age Main Sequence in 0.5–1 Myr

The final stars are massive (500–1000 $M_{\odot}$), bright ($10^6$–$10^7$ $L_{\odot}$), and cool ($T_{\text{eff}}<10^4$K)
Current questions

• What is the *detailed structure and evolution* of a Dark Star?

• *How long* can a Dark Star capture dark matter?

• How do Dark Stars modify the *reionization history of the universe*?

• How do Dark Stars change the production of heavy elements and the *chemical abundances of the oldest stars*?

• Do Dark Stars evolve into *intermediate-mass or supermassive black holes* that grow into high-redshift quasars?

• Can Dark Stars power *gamma-ray bursts* at high redshift?

• How can we *observe* Dark Stars? JWST, neutrinos, gamma-rays?

• What about *non-WIMP dark matter*?