Constraints on Axion-Like Particles from a Hard X-ray Observation of Betelgeuse

Mengjiao Xiao, MIT
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Based on the work: M. Xiao, K. Perez, M. Giannotti, O. Straniero, A. Mirizzi, B. Grefenstette, B. Roach, M. Nynka. Phys. Rev. Letts 126, 031101 (2021)
Axions & Axion-Like Particles

- Strongly motivated to solve strong CP problem of the Standard Model.

$$L = \ldots + \frac{a}{f_a} \frac{g^2}{32 \pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \frac{1}{2} \partial_\mu a \partial^\mu a + \ldots$$

$$\theta = \frac{a}{f_a} \quad \text{relaxes to zero} \quad (|\theta| < 10^{-10} \text{ from neutron EDM})$$

- Axion-like particles (ALPs): predicted by many extensions of the Standard Model (e.g. string theory)

- May solve the dark matter problem for free.
May weakly couple to many particles in SM (gluons/quarks, and photons)

- ALP-photon coupling promising (naturally) for detection

Significant unexplored parameter space, experimental efforts growing fast!

C. O’Hare. Github
ALP Telescope Principle

Massive Stars as ALP Factories

Galactic Magnetic Field

Space Telescopes

ALP Production Rate (Primakoff process)

ALP-Photon Conversion Probability ($P_{\alpha\gamma}$)

Detector Response

Observed Signal Rate

$$\mathcal{L}_{\alpha\gamma} = -\frac{1}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} a = \mathbf{E} \cdot \mathbf{B} a$$

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Betelgeuse as ALP Factory

Alpha Orionis (Betelgeuse): red supergiant in the constellation of Orion.

- Well studied:
  - $\log L/L_\odot = 5.10 \pm 0.22$  
    \[ T. Le Bertre et al. (2012) \]
  - $T_{eff} = 3641 \pm 53$ K  
    \[ G. Perrin et al. (2004) , E. Levesque & P. Massey (2020) \]
  - $M \sim 20 M_\odot$  
    \[ M. Dolan et al, Astro-phys. J. 819, 7 (2016) \]

- Advanced stage

- Near (200 pc)  
  \[ G. Harper et al. (2008) (2017) \]

- No solar-like corona that could emit X-rays  
  \[ J. Posson-Brown et al. arXiv:astro-ph/0606387 \]

- There are no bright sources within 5°, ensuring no significant stray light contamination

- Other observations (Chandra, soft X-rays) exist  
  \[ J. Posson-Brown et al. arXiv:astro-ph/0606387 \]
Betelgeuse: ALP-photon Production

- **ALP production rate:**

\[
\frac{dN_a}{dE} = \frac{10^{64}}{\text{keV s}} \cdot C \cdot g_{a\gamma}^2 \cdot \left( \frac{E}{E_0} \right)^\beta \cdot e^{-\frac{(\beta+1)E}{E_0}}
\]

Parameterized by stellar model

- **t_{cc}:** time until core collapse for Betelgeuse, modeled from 1.4 yr to 1.55×10^5 yr

- **ALP-photon conversion probability:**

\[
P_{a\gamma} = 8.7 \times 10^{-6} \left( \frac{g_{a\gamma}}{10^{-11}} \right)^2 \left( \frac{B_T}{1 \mu G} \right)^2 \left( \frac{d}{197 \text{ pc}} \right)^2 \frac{\sin^2 q}{q^2}
\]

\[
q = [77 \left( \frac{m_a}{10^{-10} \text{ eV}} \right)^2 - 0.14 \left( \frac{n_e}{0.013 \text{ cm}^{-3}} \right)] \times \left( \frac{d}{197 \text{ pc}} \right) \left( \frac{E}{1 \text{ keV}} \right)^{-1}
\]

- **B_T:** Assuming homogeneous regular, 0.4~3.0 μG

R. Jansson et al. (2012)
J. Xu et al. (2019)
L. Harvey-Smith et al. (2011)
Betelgeuse: ALP-photon Production

Predicted ALP-photon Flux: \( \frac{dN_a}{dE} \times P_{a\gamma} \propto B_T^2 \cdot g_{a\gamma}^4 \)

- Expected event counts from ALP-photon conversion from Betelgeuse for 13 stellar models
  - \( m_a = 10^{-11} \) eV
  - \( B_T = 1.4 \) \( \mu G \)
  - \( g_{a\gamma} = 1.5 \times 10^{-11} \) GeV\(^{-1} \)

Marked as Hard X-ray range!
**NuSTAR Satellite Telescope**

- **NuSTAR**: NUclear Spectroscopic Telescope Array, launched in 2012.

- Two identical telescopes, independent optic and focal-plane detector (FPMA/FPMB)
  - Each FOV 13′×13′, with a half-power diameter of ∼60″ for a point source near the optical axis.

- Best existing instrument to detect the **hard X-rays** (3–79 keV) in space!

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F.A. Harrison et al. ApJ, 770, 103 (2013)

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Betelgeuse Observation with NuSTAR

Expected event counts in NuSTAR for 13 stellar models of Betelgeuse

- Instrument response files were extracted from source region (see later)

- \( m_\alpha = 10^{-11} \text{ eV} \)
- \( B_T = 1.4 \text{ } \mu\text{G} \)
- \( g_{\alpha\gamma} = 1.5 \times 10^{-11} \text{ GeV}^{-1} \)
Betelgeuse Observation with NuSTAR

- First hard X-ray observations of Betelgeuse, using NuSTAR (~50 ks, taken on Aug. 23, 2019, ObsID 30501012002)
  - NASA Grant No. 80NSSC20K0031

- **Source Region**: $r=60^\prime\prime$ around the star’s equatorial coordinates (RA=88.79293°, Dec.=7.40706°)

- **Background Region**:
  - On the same detector chip as the source region (to properly describe spatially-varying backgrounds).
  - Separated from source region center by at least $120^\prime\prime$ and at least $60^\prime\prime$ from one point source (Chandra source CXOJ055520:2+072002).

- FPMA image of NuSTAR observation regions in the energy range 3-79 keV

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Data Analysis

- Data were processed with the standard NuSTAR data reduction pipeline

- **Source spectrum**: extracted from the source region with NUPRODUCTS
  - *Instrument response files (ARF/RMF) were extracted simultaneously*

- **Background (N_{bkg})**: normalized the background spectrum to source region size
Data Analysis

- Data were processed with the standard NuSTAR data reduction pipeline

- **Source spectrum:** extracted from the source region with NUPRODUCTS
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- **Background** ($N_{bkg}$): normalized the background spectrum to source region size

```
| Photon Energy | FPMA   | FPMB   |
|---------------|--------|--------|
|               | $N_{obs}$ | $N_{bkg}$ | $N_{obs}$ | $N_{bkg}$ |
| 10—60 keV     | 313     | 315.8  | 352      | 362.7    |
| 10—70 keV     | 354     | 359.8  | 397      | 406.4    |
| 10—79 keV     | 384     | 392.7  | 433      | 441.2    |
```

- No significant excess of events above the expected background was found!
Profile likelihood analysis approach was performed to fit the data.

For FPMA/FPMB, an unbinned likelihood function was constructed:

\[
\mathcal{L}_i = \text{Poisson}(N_{\text{obs}} | N_{\text{exp}}) \times \prod_{j=1}^{N_{\text{obs}}} \left[ \frac{N_{\text{ax}} P_{\text{ax}}(E_j^\gamma)}{N_{\text{exp}}} + \frac{N_{\text{bkg}}(1 + \delta_{\text{bkg}}) P_{\text{bkg}}(E_j^\gamma)}{N_{\text{exp}}} \right]
\]

Combined data sets from FPMA and FPMB were fitted to set the final upper limit on \( g_{\alpha\gamma} \) (for an assumed \( B_T \) and \( t_{cc} \)).

\[
\mathcal{L} = \prod_{i=1}^{n} \mathcal{L}_i \times \prod_{i=1}^{n} \text{Gauss}(\delta_{\text{bkg}}^i, \sigma_{\text{bkg}}^i)
\]

\( B_T = 1.4 \, \mu G \)
Constraints on the ALPs

- A new competitive bound (95% C.L.) from the hard X-ray observation of Betelgeuse with NuSTAR, a factor of ~3x stronger than CAST at low mass.

- $0.4 \, \mu G \leq B_T \leq 3.0 \, \mu G$

- $1.4 \, yr \leq t_{cc} \leq 1.55 \times 10^5 \, yr$

- $g_{a\gamma} < (0.5-1.8) \times 10^{-11} \, GeV^{-1}$ (depending on magnetic field and Betelgeuse stellar model) for ALP masses $m_a < (5.5-3.5) \times 10^{-11} \, eV$

*Similar study with other stellar objects: C. Dessert et al. (2020)*
Constraints on the ALPs

- Compare to other astrophysical constraints in the low-mass ALP regime.
  - Each constraint has unique sources of systematic errors.

- The combination of various astrophysical constraints builds confidence in the robustness of the exclusion!

*Similar study with other stellar objects: C. Dessert et al. (2020)*
More Discussion

- Evolution of $g_{a\gamma}$ with the remaining time until the core-collapse ($t_{cc}$) for Betelgeuse.

**Benefit:** if future ALP experiments discover ALPs in the region our optimistic case excludes, we would set a lower limit on $t_{cc}$ for Betelgeuse.
Thank You!
Backup Slide: observation images
Backup Slide: observation data

- **FPMA background (before normalization)**
- **FPMA background (after normalization)**
- **FPMA Betelgeuse (r=60")**
- **FPMB background (before normalization)**
- **FPMB background (after normalization)**
- **FPMB Betelgeuse (r=60")**

**Counts/keV**

- $t_{cc} = 3.6$ yr
- $t_{cc} = 730$ yr
- $t_{cc} = 23,000$ yr

**FPMA after background subtraction**
**FPMB after background subtraction**

**X-ray Energy [keV]**
Backup Slide: background regions

(a) FPMA

(b) FPMB
Backup Slide: more ALP-photon flux

\[ m_\alpha = 1.0 \times 10^{-10} \text{ eV (before NuSTAR)} \]

\[ m_\alpha = 2.0 \times 10^{-10} \text{ eV (before NuSTAR)} \]

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Data were processed with the standard NuSTAR data reduction pipeline

- NuSTARDAS v1.8.1 distributed in HEASOFT v6.24
- Latest calibration package (CALDB.indx20191219)
- SAAMODE=OPTIMIZED and TENTACLE=YES

**Source spectrum:** extracted from the source region with NUPRODUCTS

- Instrument response files (ARF/RMF) were extracted simultaneously

**Background** \( N_{bkg} \): normalized the background spectrum to source region size

| Photon Energy | FPMA | FPMB |
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| \( N_{obs} \) | \( N_{bkg} \) | \( N_{obs} \) | \( N_{bkg} \) |
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### NuSTAR Satellite Telescope

| Parameter                                      | Value                        |
|------------------------------------------------|------------------------------|
| Energy range                                   | 3–78.4 keV                   |
| Angular resolution (HPD)                       | 58″                          |
| Angular resolution (FWHM)                      | 18″                          |
| FoV (50% resp.) at 10 keV                     | 10′                          |
| FoV (50% resp.) at 68 keV                     | 6′                           |
| Sensitivity (6–10 keV) (10^6 s, 3σ, ΔE/E = 0.5) | 2 × 10^{-15} erg cm^{-2} s^{-1} |
| Sensitivity (10–30 keV) (10^6 s, 3σ, ΔE/E = 0.5)| 1 × 10^{-14} erg cm^{-2} s^{-1} |
| Background in HPD (10–30 keV)                  | 1.1 × 10^{-3} counts s^{-1}   |
| Background in HPD (30–60 keV)                  | 8.4 × 10^{-4} counts s^{-1}   |
| Energy resolution (FWHM)                       | 400 eV at 10 keV, 900 eV at 68 keV |
| Strong source (>10σ) positioning               | 1′.5 (1σ)                    |
| Temporal resolution                            | 2 μs                         |
| Target of opportunity response                 | <24 hr                       |
| Slew rate                                      | 0:06 s^{-1}                  |
| Settling time                                  | 200 s (typ)                  |

| Focal Plane Parameter                          | Value                        | Focal Plane Parameter                          | Value                      |
|------------------------------------------------|------------------------------|------------------------------------------------|-----------------------------|
| Pixel size                                     | 0.6 mm/12″3                  | Max. processing rate                            | 400 events s^{-1} module^{-1} |
| Focal plane size                               | 12′ × 12′                    | Max. flux meas. rate                            | 10^4 counts s^{-1}          |
| Hybrid format                                  | 32 pix × 32 pix              | Time resolution (relative)                      | 2 μs                       |
| Energy threshold                               | 2 keV                        | Dead time fraction (at threshold)               | 5%                         |
**ALP production rate:**

\[
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\]

**ALP-photon conversion probability:**

\[
P_{\alpha\gamma} = 8.7 \times 10^{-6} \left( \frac{g_{\text{ay}}}{10^{-11}} \right)^2 \left( \frac{B_T}{1 \ \mu G} \right)^2 \left( \frac{d}{197 \ pc} \right)^2 \frac{\sin^2 q}{q^2} \times [77 \left( \frac{m_a}{10^{-10} \ eV} \right)^2 - 0.14(\frac{n_e}{0.013 \ cm^{-3}})] \times \left( \frac{d}{197 \ pc} \right) \left( \frac{E}{1 \ keV} \right)^{-1}
\]

Parameterized by stellar model

(Assuming homogeneous regular B field)

| Model | Phase                  | \(t_{cc} \) [yr] | \(\log_{10}(L_{\text{eff}}/L_\odot)\) | \(\log_{10}(T_{\text{eff}}/K)\) | \(C\)  | \(E_0 \) [keV] | \(\beta\) |
|-------|------------------------|------------------|---------------------------------|---------------------------------|-------|----------------|--------|
| 0     | He burning             | 155000           | 4.90                           | 3.572                           | 1.36  | 50             | 1.95   |
| 1     | before C burning       | 23000            | 5.06                           | 3.552                           | 4.0   | 80             | 2.0    |
| 2     | before C burning       | 13000            | 5.06                           | 3.552                           | 5.2   | 99             | 2.0    |
| 3     | before C burning       | 10000            | 5.09                           | 3.549                           | 5.7   | 110            | 2.0    |
| 4     | before C burning       | 6900             | 5.12                           | 3.546                           | 6.5   | 120            | 2.0    |
| 5     | in C burning           | 3700             | 5.14                           | 3.544                           | 7.9   | 130            | 2.0    |
| 6     | in C burning           | 730              | 5.16                           | 3.542                           | 12    | 170            | 2.0    |
| 7     | in C burning           | 480              | 5.16                           | 3.542                           | 13    | 180            | 2.0    |
| 8     | in C burning           | 110              | 5.16                           | 3.542                           | 16    | 210            | 2.0    |
| 9     | in C burning           | 34               | 5.16                           | 3.542                           | 21    | 240            | 2.0    |
| 10    | between C/Ne burning   | 7.2              | 5.16                           | 3.542                           | 28    | 280            | 2.0    |
| 11    | in Ne burning          | 3.6              | 5.16                           | 3.542                           | 26    | 320            | 1.8    |
| 12    | beginning of O burning | 1.4              | 5.16                           | 3.542                           | 27    | 370            | 1.8    |

- \(t_{cc}\): time until core collapse for Betelgeuse

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Backup Slide: Betelgeuse-Chandra

- ObsID: 3365
- Energy range: 0.3-8 keV
- Exposure time: 4.899 ks