Searching for Highly Magnified Stars at Cosmological Distances: Discovery of a Redshift 0.94 Blue Supergiant in Archival Images of the Galaxy Cluster MACS J0416.1-2403

Wenlei Chen,1 Patrick L. Kelly,1 Jose M. Diego,2 Masamune Oguri,3,4,5 Liliya L. R. Williams,1 Adi Zitrin,6 Tommaso L. Treu,7 Nathan Smith,8 Thomas J. Broadhurst,9,10,11 Nick Kaiser,12 Ryan J. Foley,13 Alexei V. Filippenko,14,15 Laura Salo,16 Jens Hjorth,17 and Jonatan Selsing18

ABSTRACT

Individual highly magnified stars have been recently discovered at lookback times of more than half the age of the Universe, in lensed galaxies that straddle the critical curves of massive galaxy clusters. Having confirmed their detectability, it is now important to carry out systematic searches for them in order to establish their frequency, and in turn learn about the statistical properties of high-redshift stars and of the granularity of matter in the foreground deflector. Here we report the discovery of a highly magnified star at redshift z = 0.94 in a strongly lensed arc behind a Hubble Frontier Field galaxy cluster, MACS J0416.1-2403, discovered as part of a systematic archival search. The bright transient (dubbed “Warhol”) was discovered in Hubble Space Telescope data taken on 2014 September 15 and 16. This single image faded over a period of two weeks, and observations taken on 2014 September 1 show that the duration of the microlensing event was at most four weeks in total. The light curve may also exhibit slow changes over a period of years consistent with the level of microlensing expected from stars responsible for the intracluster light (ICL) of the cluster. Optical and infrared observations taken near peak brightness can be fit by a stellar spectrum with moderate host-galaxy extinction. A blue supergiant matches the measured spectral energy distribution near peak, implying a temporary magnification of at least several thousand. While the spectrum of an O-type star would also fit the transient’s spectral energy distribution, extremely luminous O-type stars are much less common than blue supergiants. The short timescale of the event and the estimated effective temperature indicate that the lensed source is an extremely magnified star.

On the Observability of Individual Population III Stars and Their Stellar-mass Black Hole Accretion Disks through Cluster Caustic Transits

Rogier A. Windhorst1, F. X. Timmes1, J. Stuart B. Wyithe1, Mehmet Alpaslan2, Stephen K. Andrews4, Daniel Coe5,6, Jose M. Diego6,7, Mark Dijkstra7, Simon P. Driver7, Patrick L. Kelly1,7, and Duho Kim1

Abstract

We summarize panchromatic Extragalactic Background Light data to place upper limits on the integrated near-infrared surface brightness (SB) that may come from Population III stars and possible accretion disks around their stellar-mass black holes (BHs) in the epoch of First Light, broadly taken from \( z \approx 7–17 \). Theoretical predictions and recent near-infrared power spectra provide tighter constraints on their sky signal. We outline the physical properties of zero-metallicity Population III stars from MESA stellar evolution models through helium depletion and of BH accretion disks at \( z \gtrsim 7 \). We assume that second-generation non-zero-metallicity stars can form at higher multiplicity, so that BH accretion disks may be fed by Roche-lobe overflow from lower-mass companions. We use these near-infrared SB constraints to calculate the number of caustic transits behind lensing clusters that the James Webb Space Telescope and the next-generation ground-based telescopes may observe for both Population III stars and their BH accretion disks. Typical caustic magnifications can be \( \mu \approx 10^4–10^5 \), with rise times of hours and decline times of \( \lesssim 1 \) year for cluster transverse velocities of \( v_T \lesssim 1000 \) km s\(^{-1}\). Microlensing by intracluster-medium objects can modify transit magnifications but lengthen visibility times. Depending on BH masses, accretion-disk radii, and feeding efficiencies, stellar-mass BH accretion-disk caustic transits could outnumber those from Population III stars. To observe Population III caustic transits directly may require monitoring 3–30 lensing clusters to \( AB \lesssim 29 \) mag over a decade.
Virtues of High Redshift Cluster Lensing

Source detection limit of HST/JWST is 28-30 mag

Distance modulus to objects at $z = 1$ or 2 is 43-45

A star with $M = 0$ (e.g. Arcturus) will be 43-45 mag

Brightest normal supergiants ($M = -12$) will be 31-33 mag

Add a gravitational lens with factor 1000x gain:

Supergiants will be 24-26 mag – EASILY DETECTABLE

Do such lenses exist?
Searching for Highly Magnified Stars at Cosmological Distances: Discovery of a Redshift 0.94 Blue Supergiant in Archival Images of the Galaxy Cluster MACSJ0416.1-2403

WENLEI CHEN,1 PATRICK L. KELLY,1 JOSE M. DIEGO,2 MASAMUNE OGURI,3,4,5 LIILYA L. R. WILLIAMS,1 ADI ZITRIN,6 TOMMASO L. TREU,7 NATHAN SMITH,8 THOMAS J. BRODHURST,9,10,11 NICK KAISER,12 RYAN J. FOLEY,13 ALEXEI V. FILIPENKO,14,15 LAURA SALO,16 JENS HJORST,17 AND JONATAN SELSING18

1 School of Physics and Astronomy, University of Minnesota, 116 Church Street SE, Minneapolis, MN 55455, USA
2 IFCA, Instituto de Física de Cantabria (UC-CSIC), Av. de Los Castros s/n, 39005 Santander, Spain
3 Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
4 Research Center for the Early Universe, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
5 Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI), University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8583, Japan
6 Physics Department, Ben-Gurion University of the Negev, P.O. Box 653, Beer-Sheva 8410501, Israel
7 Department of Physics and Astronomy, University of California, Los Angeles, CA 90095
8 Department of Astronomy, University of Arizona, Tucson, AZ 85721, USA
9 Department of Theoretical Physics, University of the Basque Country UPV/EHU, 48080 Bilbao, Spain
10 Donostia International Physics Center (DIPC), 20018 Donostia, Spain
11 Ikerbasque, Basque Foundation for Science, E-48011 Bilbao, Spain
12 Département de Physique, École Normale Supérieure, Paris
13 Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA
14 Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA
15 Miller Senior Fellow, Miller Institute for Basic Research in Science, University of California, Berkeley, CA 94720
16 Department of Physics, Hillsdale College, 33 E. College St., Hillsdale, MI 49242, USA
17 DARK, Niels Bohr Institute, University of Copenhagen, Lyngbyvej 2, DK-2100 Copenhagen, Denmark
18 The Cosmic Dawn Center (DAWN), Niels Bohr Institute, University of Copenhagen, Lyngbyvej 2, DK-2100 Copenhagen 0, Denmark; DTU-Space, Technical University of Denmark, Elektrovej 327, DK-2800 Kongens Lyngby, Denmark

Submitted to ApJ

ABSTRACT

Individual highly magnified stars have been recently discovered at lookback times of more than half the age of the Universe, in lensed galaxies that straddle the critical curves of massive galaxy clusters. Having confirmed their detectability, it is now important to carry out systematic searches for them in order to establish their frequency, and in turn learn about the statistical properties of high-redshift stars and of the granularity of matter in the foreground deflector. Here we report the discovery of a highly magnified star at redshift $z = 0.94$ in a strongly lensed arc behind a Hubble Frontier Field galaxy cluster, MACSJ0416.1-2403, discovered as part of a systematic archival search. The bright transient (dubbed “Warhol”) was discovered in Hubble Space Telescope data taken on 2014 September 15 and 16. This single image faded over a period of two weeks, and observations taken on 2014 September 1 show that the duration of the microlensing event was at most four weeks in total. The light curve may also exhibit slow changes over a period of years consistent with the level of microlensing expected from stars responsible for the intracluster light (ICL) of the cluster. Optical and infrared observations taken near peak brightness can be fit by a stellar spectrum with moderate host-galaxy extinction. A blue supergiant matches the measured spectral energy distribution near peak, implying a temporary magnification of at least several thousand. While the spectrum of an O-type star would also fit the

Corresponding author: Wenlei Chen
chen6339@umn.edu

transient’s spectral energy distribution, extremely luminous O-type stars are much less common than blue supergiants. The short timescale of the event and the estimated effective temperature indicate that the lensed source is an extremely magnified star.

Keywords: gravitational lensing: strong — galaxies — clusters: general, individual: MACS J0416.1-2403

Hubble Frontier Field Clusters

1. INTRODUCTION

In 2016 May, imaging of a Hubble Frontier Field (HFF) galaxy-cluster field, MACS J1149.5+2223 (MACS1149; redshift \( z = 0.54 \)), revealed a several-week-long transient \( (F_{125W} - J) \approx 25.7 \) mag AB; \( i \approx 26.4 \) mag AB at peak) in a highly magnified galaxy at \( z = 1.49 \) (Kelly et al. 2018). A highly magnified image of the lensed star has always been detected in deep Hubble Space Telescope (HST) observations, and the spectral energy distribution (SED) of the star measured in HFF imaging in 2014 matches that of the bright transient detected in 2016 May, consistent with temporarily increased magnification. The SED also exhibits a strong Balmer jump present in some luminous stars yet absent from stellar outbursts. Finally, simulations of microlensing of a background star by stars or remnants in the foreground cluster can produce light curves similar to that observed (Diego et al. 2018; Kelly et al. 2018; Venumadhav et al. 2017). The discovery of the star realized a theoretical prediction that individual stars at cosmological distances could become sufficiently magnified to be detected (Miralda-Escude 1991).

In 2014 January and August, the FrontierSN project (PI S. Rodney) detected a pair of transients dubbed the “Spock” events at two separate locations in a highly magnified galaxy at \( z = 1.01 \) behind the MACS J0416.1-2403 (MACS0416; Ebeling et al. 2001) galaxy cluster \( (z = 0.397) \) using HST. These events, whose locations are shown in Fig. 1, were identified during two month-long campaigns to image MACS0416 as part of HFF project (PI J. Lotz). While the events each lasted only several weeks, their interpretation was not immediately apparent. The detection of the lensed star in MACS J1149 magnified by > 2000 at peak brightness prompted the interpretation of the two MACS0416 events as likely microlensing events (Rodney et al. 2018).

As shown in Fig. 1, we have now identified a third highly magnified star in the MACS0416 field in a different lensed galaxy at \( z = 0.94 \) in archival HST imaging taken in 2014 September. We have named this transient “Warhol” given its “fifteen minutes of fame.” Fig. 2 shows that the transient is within a small fraction of an arcsecond from the location of the MACS0416 cluster’s critical curve according to published models. At these small separations from the critical curve, microlensing of bright stars in a background arc by objects in the foreground cluster including stars or remnants is not only possible, but in fact inevitable.

In Section 2, we describe the imaging data in this paper. Section 3 provides the details of the methods we use to analyze the HST imaging. In Section 4, the results of our analysis are presented, and our conclusions are given in Section 5. All magnitudes are in the AB system (Oke & Gunn 1983), and we use a standard set of cosmological parameters (\( \Omega_m = 0.3, \Omega_\Lambda = 0.7, H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\)).

2. DATA

Imaging of the MACS0416 galaxy-cluster field with the ACS and WFC3 cameras has been acquired as part of the Cluster Lensing and Supernova survey with Hubble (CLASH; GO-12459; Postman et al. 2012), the Grism Lens-Amplified Survey from Space (GLASS; PI T. Treu; GO-13459; Schmidt et al. 2014; Treu et al. 2015), the HFF (GO-13496; Lotz et al. 2017), the FrontierSN follow-up program (PI S. Rodney; GO-13386), and the Final UV Frontier project (PI Siana; GO-14209). Earlier imaging of the MACS0416 field, not analyzed in this paper, was acquired with the WFCPC2 (PI H. Ebeling; GO-11103). The microlensing peak we report here occurred in the target-of-opportunity imaging follow-up of the Spock events (Rodney et al. 2018) acquired by the FrontierSN program.

3. METHODS

3.1. Image Processing and Coaddition

We aligned all imaging with TweakReg, and then resampled images to a scale of 0.03” pixel\(^{-1}\) using AstroDrizzle (Fruchter et al. 2010).

3.2. PythonPhot Photometry

We use PythonPhot\(^1\) (Jones et al. 2015) to measure the light curves from difference imaging. The PythonPhot package includes an implementation of point-spread function (PSF) fitting photometry based on the DAOPHOT algorithm (Stetson 1987).

4. RESULTS

\(^1\) https://github.com/djones1040/PythonPhot
Figure 1. Left panel shows the location of the newly discovered extremely magnified star in an arc at $z = 0.94$ found in archival HST imaging of the MACS0416 galaxy cluster, and the positions of the two stellar microlensing events previously identified by Rodney et al. (2018) in a different strongly lensed galaxy at $z = 1.01$. The timescales of all three events were several weeks. Right panel shows an example deep template WFC3-IR F160W image of the field (top), image of the newly identified event near peak in 2014 September (middle), and the difference image (bottom).

4.1. Position and Underlying Arc

The transient’s J2000 coordinates are $\alpha = 4h16m08.7084^s$, $\delta = -24^\circ04'02.945''$ in the World Coordinate System (WCS) of the official HFF coadded images. A spectrum of the underlying arc acquired by the CLASH-VLT survey yielded $z = 0.93910$ (Balestra et al. 2016; Caminha et al. 2017). The smaller redshift of the arc (compared with the previous examples of lensed stars) implies that fainter stars can be magnified above the detection threshold. Patrício et al. (2018) measure an oxygen abundance of $12 + \log(O/H) = 8.72 \pm 0.6$ dex and a low extinction of $A_V = 0.15 \pm 0.20$ from nebular emission lines for the lensed system from Multi Unit Spectroscopic Explorer (MUSE) integral-field unit (IFU) spectroscopy.

4.2. Magnification Predictions for Galaxy-Cluster Models

We calculate magnification maps at $z = 0.94$ using ten independent Frontier Fields Lens Models (Lotz et al. 2017) for the MACS0416 galaxy cluster, as shown in Fig. 2. The predicted magnification $\mu$ due to the galaxy-cluster lens at Warhol’s position is listed in Table 2. In general, the locations of galaxy-cluster critical curves are constrained by current models to within several tenths of an arcsecond in the best cases. Given Warhol’s proximity to the critical curve, the uncertainty in the critical curve’s location results in a large magnification uncertainty at its position.

4.3. Light Curve and Duration of Event

The optical and near-infrared light curve plotted in Fig. 3 shows that the microlensing event faded over a period of at least two weeks. The event was at least $\sim 1.5$ times brighter (total flux) in the infrared (IR) band than its underlying arc in archival HST imaging during the HFF project, as the true peak of this microlensing event may have occurred during gaps of HST visits, as shown in Fig. 3. Photometry is measured using a 0.2'' aperture (detailed values are listed in Table 3).

A microlensing peak should have a duration roughly $R/v$, where $R$ is the size of the lensed source and $v$ is the transverse velocity of the lensing system. Given the $\sim 1000$ km s$^{-1}$ expected relative transverse velocity between the galaxy cluster and background source, the several-week timescale of the microlensing peaks implies that the lensed sources can only extend for at most several tens of AU. Consequently, the lensed systems must be
**Figure 4.** Left panel: Example of the lensing magnification map for galaxy cluster MACS J1149.5+2223 at $z \approx 0.4$ and a background source at $z = 10$ (e.g., Lotz et al. 2017 and references therein). Light from the cluster galaxies is not shown to avoid overcrowding, but can be found in these papers. The white areas mark the critical curves, where the maximum lensing magnification is observed from this cluster for a background source with half-light radius $r_{\text{hl}} \lesssim 0'5$ at $z = 10$. The lightest regions have the highest magnification ($\mu \gtrsim 10$–20), while the darkest regions are areas of low magnification ($\mu \approx 1$ or even $\mu \lesssim 1$) around the cluster member galaxies. Right panel: Example of the caustic map produced by the cluster mass model for a background source at $z = 10$. This is the location where a point source at $z = 10$ produces maximum magnification. The total length of the cluster caustics can be as large as $L \approx 100''$, which we adopt as upper limit to the typical caustic length in our caustic transits calculations.

Left: bright lines = “critical curves” (maximum magnification) as seen in image plane

Right: “caustics” in source plane where objects will fall on CC’s

- CC locations/mag depend on distances to lens and to source and on diameter of source
- CC locations move as cluster or its components move across the sky
- Magnification is always time-variable
stellar systems (e.g., single star or binary system) instead of a star cluster.

4.4. A Single-Image Transient Event

Sources near a cluster fold caustic (with no microlenses) should appear as a pair of images with equal magnification. Therefore, if the new transient were a stellar outburst, we would expect to see a pair of transients with a relative time delay of less than a day. By contrast, a microlensing event should only appear as a single transient, as a star or remnant in the cluster becomes temporarily aligned with one of the magnified images of the background star. As shown in Fig. 6, only a single bright transient along the arc was detected during the 2014 September HST visits.

4.5. A Counterimage of the Lensed Star?

Warhol's location, marked by the green circle labeled “A” in Fig. 6, corresponds to a peak along the underlying arc in coadditions of HFF F606W and F814W imaging acquired before the microlensing event. To determine whether a counterimage of the underlying source may exist along the arc, we measured the flux inside of a 0.05″ diameter aperture as we moved it along the arc. Fig. 7 shows possible evidence for a second peak labeled “B” along the underlying arc. The locations A and B are separated by ~0.12″. In the absence of microlensing, the fluxes of two counterimages should be identical. Therefore, the fact that two observed potential counterimages do not exhibit equal fluxes implies the presence of microlensing.

4.6. Spectral Energy Distribution of the Star

After correcting for extinction expected for the Galactic foreground ($A_V = 0.112$ mag; Schlafly & Finkbeiner 2011), we fit the spectral energy distribution (SED) of the microlensing peak. ACS-WFC F606W and F814W, as well as WFC-IR F125W and F160W, imaging was acquired during a first epoch on 2014 September 15–16; the optical and IR integrations were interspersed with

Conclude: microlensing by star in cluster superposed on near-maximal cluster lensing
Figure 3. Photometry of the newly identified microlensing event identified in archival images of the MACS0416 HFF galaxy-cluster field. The upper panel shows the multiband optical and near-infrared light curve close to peak brightness in 2014 September, and shows that its timescale is on the order of several weeks, similar to those of the microlensing events reported by Kelly et al. (2018) in MACS1149 and Rodney et al. (2018) in MACS0416. A several-week duration is also consistent with the expected transverse velocities of galaxy clusters (Kelly et al. 2018; Diego et al. 2018; Venumadhav et al. 2017; Oguri et al. 2018). The lower panel plots all existing HST observations of the MACS0416 galaxy-cluster field.

Each other in time. As shown in Fig. 3, the transient was still detected during a second imaging epoch on 2014 September 22.

We simultaneously fit a Castelli & Kurucz (2004) stellar atmosphere model and a host-galaxy extinction curve to the measured SED of the Warhol microlensing event. We assume that the source did not vary significantly while the optical and IR images were acquired during the first epoch. We include as a fit parameter the change in the magnification (relative normalization of the SED) between the first and second epochs.

Fig. 4 shows the best fit to the measured photometry when we allow the temperature of the stellar photosphere to vary as a free parameter. In Fig. 5, we show that the best-fitting stellar model (with temperature $T \approx 13,600$ K) to the highly magnified blue supergiant Icarus in the MACS1149 field (Kelly et al. 2018) also provides a reasonable fit to Warhol’s SED. The low to moderate best-fitting host-galaxy dust extinction is consistent with the $A_V = 0.15 \pm 0.20$ mag extinction inferred by Patrício et al. (2018) from an analysis of nebular emission lines from the lensed galaxy. We expect that microlensing may only potentially be chromatic when a microcaustic
Figure 4. Stellar atmosphere model with temperature $\sim 40,000$ K (Castelli & Kurucz 2004) and host-galaxy extinction that provide the best fit to the measured SED during the 2014 September microlensing event. In this fit, we allow the temperature of the star to vary as a free parameter. The red points mark photometry measured from images taken on 2014 September 15 and 16. The gray points mark fluxes measured from imaging acquired on 2014 September 22; given the light curve’s evolution we include an additional parameter in the fit: the relative flux normalization of the event between September 15–16 and September 22.

Figure 5. Same as Fig. 4, except that here the stellar atmosphere (13,591 K and log $g = 4$) is one of the best-fitting models to the SED of the extremely magnified blue supergiant star Icarus in the MACS1149 field (Kelly et al. 2018). Given their lower initial masses and longer lifetimes, blue supergiants luminous in the rest-frame optical are more numerous than the most massive and luminous O-type stars.
Figure 6. *HST* imaging around Warhol’s position. Upper four panels show coadditions of *HST* images obtained from the HFF project using ACS-WFC F606W, ACS-WFC F814W, WFC3-IR F125W, and WFC3-IR F160W (templates). Middle four panels are the *HST* images during the microlensing event detected around 2014 September 15. Lower four panels are the difference images. A peak (marked by the circle “A” in the top-left panel) can be identified from the optical *HST* imaging in the arc. There may be another peak along the arc shown in the F606W band (as marked by the circle “B”). The same positions of A and B are marked by green and cyan circles (respectively) in all images. Each pair of transient and template images is displayed using the same color scale.
is close to the limb of the star, but this should occur over a very short timescale smaller than the ~2 days during which observations near peak were acquired.

4.7. Magnification

We use the definition of a K-correction $K_{xy}$ as

$$m_y = M_x + dm + K_{xy},$$

where $m_y$ is the observer-frame apparent magnitude in the $y$ band, $M_x$ is the rest-frame absolute magnitude in the $x$ band, and $dm$ is the distance modulus. To calculate a $K$-correction, we use Eq. 2 of Kim et al. (1996),

$$K = 2.5 \log_{10}(1 + z) + m_{F125W}^{AB} - m_{V,syn}^{Vega}$$

where $z = 0.94$, $m_{F125W,syn}^{AB}$ is the WFC3 $F125W$ synthetic magnitude of a redshifted model spectrum, and $m_{V,syn}^{Vega}$ is the synthetic Johnson $V$-band magnitude of the rest-frame model spectrum. Using the best-fitting spectral models, we calculate $K_{V,F125W} \approx -0.4$, and adopt $dm = 43.96 \text{mag}$ at $z = 0.94$ (with no correction for magnification).

For fold caustics, the source-plane area $A$ within which the magnification exceeds $\mu$ scales as $A(>\mu) \propto 1/\mu^2$. Consequently, low-magnification microlensing events have greater probability of occurring. In the case of Icarus, a persistent image of the lensed blue supergiant has always been detected in deep HST imaging, and the magnification is on average 300–600, with inferred microlensing magnification reaching up to 2000 during an event in 2016 (Kelly et al. 2018).

The luminosities of blue supergiant stars in the Small Magellanic Cloud (SMC) reach $M_V \gtrsim -8.8 \text{mag}$ Dachs (1970). There are examples of extremely luminous, main-sequence O-type stars such as Melnick 34 in the 30 Doradus complex in the Large Magellanic Cloud (LMC) with an absolute magnitude of $M_V = -7.9$ (Doran et al. 2013).

However, a very luminous O-type star or Wolf-Rayet stars showing H in their spectra (WHN) should be extremely rare, whereas cooler B-type supergiants at lower bolometric luminosity but similar $M_V$ will be much more common in the field of a star-forming galaxy. The comparatively small abundance of WHN stars arises from their initial masses (very approximately 100 $M_\odot$ vs. 10–20 $M_\odot$), but also the significantly longer lifetimes at the lower masses. Among binary stars, blue supergiants can also be blue stragglers from mass gainers and mergers.

For a blue supergiant star with identical temperature and luminosity, the $F125W \approx 26.25$ apparent magnitude observed for Warhol at $z = 0.94$ would require a factor $\sim 3.5$ smaller magnification than would Icarus at $z = 1.49$ given its peak apparent magnitude of $F125W \approx 25.5$. We note, however, that Warhol’s light curve likely does not include its peak brightness. In Table 1, we list the magnification required for main-sequence and post-main-sequence stars of different spectroscopic types.

4.8. Constraints on Source Size

The separation between A and its possible counterimage B is $\sim 0.12''$. Near the critical curve, the GLAFIC galaxy-cluster mass model yields the following magnification for each of the images, in the case of a smooth model (i.e., with no microlensing):}

$$\mu_{each} \approx (11 \text{arcsec})/\theta_h,$$

where $\theta_h$ is the angular distance from the critical curve. At an offset of $\theta_h \approx 0.06''$ from the galaxy-cluster critical curve, $\mu_{each} \approx 180$ ($\mu_l \approx 120$, $\mu_r \approx 1.5$), which may be a plausible location for caustic crossing given the saturation argument presented by Diego et al. (2018).

We also compute the source crossing time as

$$t_{src} \approx 0.031 - R_{source}/R_\odot \times v/(500 \text{ km s}^{-1}) \text{ days},$$

where $v$ is a transverse velocity of the cluster and $R_{source}$ is a radius of a background star that is magnified. From the light curve, we have $t_{src} < 10$ days (see Fig. 2 of Miralda-Escude 1991 to see how $t_{src}$ relates to the expected timescale of the light curve’s evolution), which yields a limit of $R_{source} < 320R_\odot$. Assuming $\mu_l = 120$ and $\mu_r = 1.5$, the maximum magnification estimated using Eq. 48 of Oguri et al. (2018) is

$$\mu_{max} \approx (4.5 \times 10^4)(M_{lens}/M_\odot)^{-1/4}(R_{source}/R_\odot)^{-1/2}.$$  

For $M_{lens} = 0.3M_\odot$ (typical mass of a star responsible for the intracluster light of the cluster), we have $\mu_{max} \approx 33,000$ for $R_{source} = 1R_\odot$, $\mu_{max} \approx 10,000$ for $R_{source} = 10R_\odot$, and $\mu_{max} \approx 3300$ for $R_{source} = 100R_\odot$, where a larger $M_{lens}$ yields a greater maximum magnification. The comparison with Table 1 suggests that normal main-sequence stars are unlikely to be observed as microlensing events, and we need to consider either blue supergiants or extremely luminous O-type stars to explain the Warhol event.

As shown in Fig. 7, the sources A and B appear to be unresolved in HFF F606W and F814W imaging acquired before the microlensing event. An approximate estimate, assuming a transversal magnification of $\sim 100$, indicates that the coincident source at positions A and B detected in HFF imaging occurred must be $\sim 3$ pc at most, so it must be a single star, stellar system, or a compact stellar cluster.

Typical intracluster star is capable of providing needed magnification.
Figure 7. ACS-WFC F606W and ACS-WFC F814W imaging of the underlying arc detected by the HFF project before 2014 September 15–16. Bottom two panels show flux along the arc with a 0.05″ diameter aperture. Vertical green and cyan lines show the positions A and B (respectively) in Fig. 6. The horizontal bars show the full width at half-maximum intensity (FWHM) of averaged PSFs in ACS-WFC F606W and ACS-WFC F814W bands.

Table 1. Magnification (µ) required for different types of stars.

<table>
<thead>
<tr>
<th>Spec. Model</th>
<th>Temp</th>
<th>$M_V$</th>
<th>F125W</th>
<th>$K$</th>
<th>$M_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSG</td>
<td>B8V</td>
<td>11749K</td>
<td>-8.5</td>
<td>34.94</td>
<td>-0.52</td>
</tr>
<tr>
<td>Extreme MS</td>
<td>O5V</td>
<td>39810K</td>
<td>-8</td>
<td>35.58</td>
<td>-0.39</td>
</tr>
<tr>
<td>MS</td>
<td>O9V</td>
<td>35481K</td>
<td>-4.00</td>
<td>39.60</td>
<td>-0.37</td>
</tr>
<tr>
<td>MS</td>
<td>B0V</td>
<td>28183K</td>
<td>-3.70</td>
<td>39.87</td>
<td>-0.39</td>
</tr>
<tr>
<td>MS</td>
<td>B1V</td>
<td>22387K</td>
<td>-3.20</td>
<td>40.33</td>
<td>-0.43</td>
</tr>
<tr>
<td>MS</td>
<td>B3V</td>
<td>19054K</td>
<td>-2.10</td>
<td>41.41</td>
<td>-0.45</td>
</tr>
<tr>
<td>MS</td>
<td>B5-7V</td>
<td>14125K</td>
<td>-2.10</td>
<td>41.38</td>
<td>-0.48</td>
</tr>
<tr>
<td>MS</td>
<td>B8V</td>
<td>11749K</td>
<td>-1.08</td>
<td>42.36</td>
<td>-0.52</td>
</tr>
</tbody>
</table>

Approximate peak magnifications are for no host-galaxy extinction and for the peak observed F125W magnitude of ~ 26.25. “MS” is an abbreviation for main sequence, and “BSG” is an abbreviation for blue supergiant. Note that high magnifications are required for typical main-sequence stars using Pickles (1998) templates. Consequently, we favor a post-main-sequence blue supergiant having $-9 \lesssim M_V \lesssim -7$, although an extreme and even less common O-type main-sequence star also provides a satisfactory fit to the SED (see Figs. 5 and 4).

Most likely source is a bright blue supergiant
Table 2. Magnifications at the location of the transient (μ) and 0.06″ from the critical curve (μ(θ_c = 0.06″)).

<table>
<thead>
<tr>
<th>Model</th>
<th>μ</th>
<th>μ(θ_c = 0.06″)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bradač (v3)</td>
<td>11</td>
<td>197</td>
<td>Hoag et al. (2016); Bradač et al. (2009, 2005)</td>
</tr>
<tr>
<td>Caminha (v4)</td>
<td>56</td>
<td>205</td>
<td>Caminha et al. (2017)</td>
</tr>
<tr>
<td>CATS (v4.1)</td>
<td>15</td>
<td>201</td>
<td>Jauzac et al. (2014); Richard et al. (2014); Jauzac et al. (2012)</td>
</tr>
<tr>
<td>Diego (v4.1)</td>
<td>25</td>
<td>250</td>
<td>Diego et al. (2005a,b, 2007, 2015)</td>
</tr>
<tr>
<td>GLAFIC (v4)</td>
<td>45</td>
<td>180b</td>
<td>Kawamata et al. (2018, 2016); Oguri (2010)</td>
</tr>
<tr>
<td>Keeton (v4)</td>
<td>369</td>
<td>304</td>
<td>McCully et al. (2014); Ammons et al. (2014); Keeton (2010)</td>
</tr>
<tr>
<td>Sharon (v4 Cor.)</td>
<td>40</td>
<td>228</td>
<td>Johnson et al. (2014); Julio et al. (2007)</td>
</tr>
<tr>
<td>Williams/GRALE (v4)</td>
<td>40b</td>
<td>250b</td>
<td>Sebesta et al. (2016); Liesenborgs et al. (2006)</td>
</tr>
<tr>
<td>Zitrin-ltm-gauss (v3)</td>
<td>100</td>
<td>331</td>
<td>Zitrin et al. (2013, 2009) (see also Merten et al. 2011, 2009)</td>
</tr>
<tr>
<td>Zitrin-nfw (v3)</td>
<td>348</td>
<td>208</td>
<td>Zitrin et al. (2013, 2009) (see also Merten et al. 2011, 2009)</td>
</tr>
</tbody>
</table>

a Magnifications predicted by MACS J0416.1-2403 lensing models. Those at the transient’s coordinates show high dispersion given the uncertainty in the location of the galaxy cluster’s critical curve.

b Obtained using updated high-resolution maps instead of the published HFF models.

5. CONCLUSIONS

In archival HST imaging taken in 2014 September, we have identified a microlensing event dubbed Warhol in a strongly lensed galaxy at z = 0.94 very close to the location of the critical curve of the foreground MACS0416 galaxy cluster at z = 0.397. The transient’s SED is consistent with the presence of a strong Balmer break, expected for blue supergiant stars, which are also the most common very luminous stars at rest-frame optical wavelengths.

The lower temperatures and densities of H-rich stellar eruptions, by contrast, generally lack a strong Balmer jump. Further evidence for a microlensing event is the absence of a second detected transient event near the critical curve, as shown in Fig. 6. Time delays should be on the order of days at small separations from the critical curve, yet no opposing image is detected. The probability that Warhol could consist of two unresolved images of an outburst is very small, given the comparatively small area in the source plane where any such eruption must occur (Kelly et al. 2018). Warhol’s spatial coincidence with the underlying source in the strongly lensed background implies it is very unlikely to be the explosion or outburst of a star in the intracluster medium.

Furthermore, long-term variation in the light curve measured at Warhol’s position is consistent with slow fluctuations expected from microlensing by objects in the MACS0416 intracluster medium.

The frequency of bright microlensing events including Icarus (Kelly et al. 2018), likely the Spock events (Rodney et al. 2018), and Warhol provide a new probe of the mass density of objects in the intracluster medium (Diego et al. 2018; Kelly et al. 2018; Venumadhav et al. 2017; Oguri et al. 2018), as well as the qualitative properties and luminosity functions of massive stars at high redshift (Kelly et al. 2018). Diego (2018) have found that ~50,000 luminous stars at redshifts between z = 1.5 and z = 2.5 should experience an average magnification exceeding 100 from lensing halos of all masses. Of these, approximately 8000 stars should have a mean magnification greater than 250 and should exhibit relatively frequent microlensing peaks. Windhorst et al. (2018) have also recently shown that high magnification during caustic-crossing events close to cluster critical curves should provide an opportunity to observe directly Population III stars at high redshifts using the James Webb Space Telescope.

Table 3. Photometry measured from HST imaging

<table>
<thead>
<tr>
<th>Date (MJD)</th>
<th>Bandpass</th>
<th>Flux (μJy)</th>
<th>σ (μJy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>56159.53</td>
<td>ACS F435W</td>
<td>-0.0068</td>
<td>0.0129</td>
</tr>
<tr>
<td>56184.75</td>
<td>ACS F435W</td>
<td>-0.0054</td>
<td>0.0336</td>
</tr>
<tr>
<td>56663.91</td>
<td>ACS F435W</td>
<td>-0.0054</td>
<td>0.0080</td>
</tr>
<tr>
<td>56665.62</td>
<td>ACS F435W</td>
<td>-0.0162</td>
<td>0.0109</td>
</tr>
<tr>
<td>56668.55</td>
<td>ACS F435W</td>
<td>0.0055</td>
<td>0.0082</td>
</tr>
<tr>
<td>56670.42</td>
<td>ACS F435W</td>
<td>-0.0049</td>
<td>0.0049</td>
</tr>
<tr>
<td>56671.94</td>
<td>ACS F435W</td>
<td>0.0025</td>
<td>0.0083</td>
</tr>
<tr>
<td>56672.47</td>
<td>ACS F435W</td>
<td>0.0184</td>
<td>0.0118</td>
</tr>
</tbody>
</table>
On the Observability of Individual Population III Stars and Their Stellar-mass Black Hole Accretion Disks through Cluster Caustic Transits

Rogier A. Windhorst1, F. X. Timmes1, J. Stuart B. Wyithe2, Mehmet Alpaslan3, Stephen K. Andrews4, Daniel Coe5, Jose M. Diego6, Mark Dijkstra7, Simon P. Driver1, Patrick L. Kelly5, and Duho Kim1

1 School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287-1404, USA; Rogier.Windhorst@asu.edu, Francis.Timmes@asu.edu
2 University of Melbourne, Parkville, VIC 3010, Australia; SWyithe@physics.unimelb.edu.au
3 New York University, Department of Physics, 726 Broadway, Room 1005, New York, NY 10003, USA
4 The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia
5 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
6 IFCA, Instituto de Física de Cantabria (UC-CSIC), Avenida de Los Castros s/n, E-39005 Santander, Spain
7 Institute of Theoretical Astrophysics, University of Oslo, NO-0315 Oslo, Norway

Received 2017 November 22; revised 2018 January 6; accepted 2018 January 10; published 2018 February 14

Abstract

We summarize panchromatic Extragalactic Background Light data to place upper limits on the integrated near-infrared surface brightness (SB) that may come from Population III stars and possible accretion disks around their stellar-mass black holes (BHs) in the epoch of First Light, broadly taken from z ≈ 7–17. Theoretical predictions and recent near-infrared power spectra provide tighter constraints on their sky signal. We outline the physical properties of zero-metallicity Population III stars from MESA stellar evolution models through helium depletion and of BH accretion disks at z > 7. We assume that second-generation non-zero-metallicity stars can form at higher multiplicity, so that BH accretion disks may be fed by Roche-lobe overflow from lower-mass companions. We use these near-infrared SB constraints to calculate the number of caustic transits behind lensing clusters that the James Webb Space Telescope and the next-generation ground-based telescopes may observe for both Population III stars and their BH accretion disks. Typical caustic magnifications can be μ ≈ 10^3–10^5, with rise times of hours and decline times of ≲ 1 year for cluster transverse velocities of v_T ≲ 1000 km s^{-1}. Microlensing by intracluster-medium objects can modify transit magnifications but lengthen visibility times. Depending on BH masses, accretion-disk radii, and feeding efficiencies, stellar-mass BH accretion-disk caustic transits could outnumber those from Population III stars. To observe Population III caustic transits directly may require monitoring 3–30 lensing clusters to AB ≲ 29 mag over a decade.

Key words: accretion, accretion disks – galaxies: clusters: general – gravitational lensing: strong – infrared: diffuse background – stars: black holes – stars: Population III

1. Introduction

In this paper, we consider if the James Webb Space Telescope (JWST; Rieke et al. 2005; Gardner et al. 2006; Windhorst et al. 2008; Beichman et al. 2012) can observe First Light objects directly. JWST’s Near-Infrared Camera (NIRCam) is expected to reach medium-deep to deep (AB ≈ 28.5–29 mag) flux limits routinely, and in ultradeep surveys perhaps as faint as AB ≈ 30–31 mag, once JWST’s on-orbit stray-light properties are mapped.

Unlensed Population III (Pop III) stars or their stellar-mass black hole (BH) accretion disks may have fluxes of AB ≈ 35–43 mag at z ≈ 7–25, and therefore are not directly detectable by JWST, not even via ordinary gravitational lensing targets (e.g., Rydberg et al. 2013), which typically have magnification factors of μ ≈ 10 or ~2.5 mag (e.g., Lotz et al. 2017). We use “μ” throughout to indicate the lensing magnification factor, and “SB” to indicate surface brightness.

However, cluster caustic transits, when a compact rest-frame UV source transits a caustic due to the cluster motion in the sky, or perhaps due to significant velocity substructure in the cluster, have great potential for magnifying such compact objects temporally by factors of μ ≈ 10^3–10^5 (e.g., Miralda-Escude 1991; Zackrisson et al. 2015; Diego et al. 2017; Kelly et al. 2017, 2018; Rodney et al. 2017). This could temporarily boost the brightness of a very compact object by μ ≈ 7.5–12.5 mag, which may render it observable by JWST. If Pop III stars—and/or their resulting BH accretion disks—are numerous enough in the sky, it is therefore possible that individual Pop III stars or their BH accretion disks are temporarily lensed by foreground cluster caustics as the cluster transit across the background Pop III target. This could render an AB ≈ 35–41.5 mag Pop III star at redshifts z ≈ 7–17 temporarily visible to a medium-deep or deep (AB ≈ 28.5–29 mag), well time-sequenced set of JWST observations.

The 2016 Planck results (Planck Collaboration et al. 2016a, 2016b, 2016d) reduced the polarization optical depth even further from earlier values—and reduced its errors—to τ ≈ 0.058 ± 0.012, thereby placing the redshift of reionization at approximately z_{reion} ≈ 7.8 ± 0.9 if it had occurred instantaneously. Sobral et al. (2015) discovered an object at z ≈ 6.7 with both a clear Lyα 1216 Å line and a possible He I 1640 Å line, which may indicate a late, pristine stellar population dominated by very hot stars, possibly Pop III stars. That is, the Pop III star epoch may have ended around z ≈ 7 and could have started very early, at z ≥ 20–40 (Trenti & Stiavelli 2009). Of course, at z ≳ 30, the luminosity distance would be very large and render most Pop III stars fainter than AB ≥ 43 mag. In the hierarchical simulations of Sarmento et al. (2017, 2018), most of the early star formation (SF) occurs between z ≈ 20, when the star-forming population consists predominantly of pristine Pop III stars, and z ≈ 7, when the population is predominantly...
Figure 1. Summary of panchromatic backgrounds relevant to possible cluster caustic transits of Pop III stars and their stellar-mass black hole accretion disks. Green dotted-dashed lines with green unfilled squares indicate the scattered and thermal zodiacal foreground of Kelsall et al. (1998). Filled green triangles indicate the panchromatic on-orbit zodiacal (labeled “Zodi”) foreground values measured by HST (Windhorst et al. 2011). Light grey unfilled triangles indicate direct measurements of the Extragalactic Background Light from low-Earth orbit or L2 (for a review, see Dwek & Krennrich 2013). Blue unfilled circles indicate the direct Pioneer spacecraft EBL values measured beyond most of the zodiacal dust at 4.6 au. Red filled circles indicate the integrated and extrapolated (to AB ≥ 30 mag) panchromatic galaxy counts (IEBL) of Driver et al. (2016 and references therein). The dashed red, green, and purple lines are IEBL model predictions for spheroids, disks, and unobscured AGNs, respectively (Andrews et al. 2017b). The solid black line is their total predicted IEBL. EBL constraints from HESS γ-ray blazars are plotted as the light grey shaded region plus its dark-blue best fit, and for MAGIC blazars as the green shaded region with its dark-green best fit. The orange unfilled circle with dotted range is our “hard” upper limit for the diffuse 1–4 μm EBL, denoted as “Diffuse EBL limit.” The orange dashed box contains our adopted upper limits on the 1–4 μm near-IR sky-SB for Pop III stars at z ≥ 7 (dark orange) and for their stellar-mass BH accretion disks at z ≥ 7 (black). The possible range in SB from Pop III objects is indicated at the level of ~1, 10, 100, and 1000 objects/arcsec². The filled orange circle indicates the approximate SB level of ~1 Pop III star/arcsec². Cluster caustic transit rates that may be observed with JWST are listed in dark orange on the left for three SB levels, ranging from ~1 caustic transit per three clusters per year to ~1 per 30 clusters if monitored over 10 years. This is the lowest rate JWST could detect in a dedicated, large multiyear program. Details are given in Sections 2–7.

for discrete objects to within 10%–20%, including random errors, count extrapolation errors, and cosmic variance that were determined through Monte Carlo simulations. For clarity, error bars are omitted from Figure 1, but these can be found in D16. The IEBL from discrete objects is thus well-determined to within ≤20% in general, as indicated by the small scatter in
Typical caustic transit rates for Pop III stars ($M > 30 \, M_\odot$) are 0.3/year/cluster at $AB < 28.5$. Rates for stellar BH accretion disks are similar.

In summary, unlensed Pop III stars or their stellar-mass BH accretion disks may have fluxes of $AB \sim 35–41.5$ mag at $z \sim 7–17$, and so will not be directly detectable by JWST. However, cluster caustic transits with magnifications of $\mu \sim 10^4–10^5$ may well render them temporarily detectable to JWST in medium-deep to deep observations ($AB \lesssim 28.5–29$ mag) on timescales of months to a year, with rise times less than a few hours. Deep and well time-sequenced observations of the best-lensing clusters carried out throughout JWST’s lifetime would fulfill its promise to the US Congress and citizens as NASA’s “First Light” telescope.