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ABUNDANCES IN THE URANIUM-RICH STAR CS 31082-001

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ABSTRACT

The recent discovery by Cayrel et al. of U in CS 31082-001 along with Os and Ir at greatly enhanced abundances but with [Fe/H] $= -2.9$ strongly reinforces the argument that there are at least two kinds of Type II supernova (SN II) sources for *r*-nuclei. One source is the high-frequency H events responsible for heavy *r*-nuclei ($A > 135$) but not Fe. The H-yields calculated from data on other ultra–metal-poor stars and the Sun provide a template for quantitatively predicting the abundances of all other *r*-elements. In CS 31082-001 these should show a significant deficiency at $A < 135$ relative to the solar *r*-pattern. It is proposed that CS 31082-001 should have had a companion that exploded as an SN II H event. If the binary survived the explosion, this star should now have a compact companion, most likely a stellar-mass black hole. Comparison of abundance data with predicted values and a search for a compact companion should provide a stringent test of the proposed *r*-process model. The U-Th age determined by Cayrel et al. for CS 31082-001 is, to within substantial uncertainties, in accord with the *r*-process age determined from solar system data. The time gap between the big bang and the onset of normal star formation allows *r*-process chronometers to provide only a lower limit on the age of the universe.

Subject headings: nuclear reactions, nucleosynthesis, abundances — stars: individual (CS 31082-001)

1. INTRODUCTION

Recently, Cayrel et al. (2001) reported discovery of U along with a strong overabundance of the heavy *r*-process elements Os and Ir in the ultra–metal-poor (UMP; with [Fe/H] ≈ -3) halo star CS 31082-001. This star (hereafter the U-star) has [Fe/H] $= -2.9$ and is similar in certain characteristics to another UMP halo star, CS 22892-052, which has [Fe/H] $= -3.1$ and also exhibits a large enhancement of heavy *r*-elements relative to Fe. The possible use of ^{238}U as a cosmochronometer was emphasized by Cayrel et al. (2001). Their data on the U-star also have important implications for stellar sites of the *r*-process and for nucleosynthetic yields of an *r*-process event. In this Letter we argue that the observed abundances of Os, Ir, Th, and U in the U-star are the result of the most frequent Type II supernova (SN II) events and that the abundances of other *r*-elements can be predicted by a three-component model for abundances in metal-poor stars (Qian & Wasserburg 2001, hereafter QW). We also argue that the *r*-abundances in the U-star most likely reflect the contamination of its surface by the ejecta from the SN II explosion of a previous massive binary companion. If the binary survived the explosion, the U-star should now have a compact companion, most likely a stellar-mass black hole. These inferences could be directly tested by further observations of the U-star. We also show that the U-Th age of halo stars provides an estimate for the "local" onset of *r*-process nucleosynthesis, which sets only a lower bound on the age of the universe.

The approach here follows that used by QW to develop the three-component model for abundances in metal-poor stars based on the abundances of the radioactive nuclei ^{129}I and ^{182}Hf in the early solar system. These abundances require two distinct types of SNe II if the *r*-process is associated with such events. The two types are the H and L events (Wasserburg, Busso, & Gallino 1996; Qian, Vogel, & Wasserburg 1998; Qian & Wasserburg 2000). The H events occur at a "high" frequency of $\approx(10^7\ \mathrm{yr})^{-1}$ in a standard reference mass of interstellar medium (ISM; mostly hydrogen) and are the major source of "heavy" *r*-nuclei (with mass number $A > 135$). The L events occur at a "low" frequency of $\approx(10^8\ \mathrm{yr})^{-1}$ and are the major source of "light" *r*-nuclei (with $A < 135$). It was predicted that UMP stars would exhibit peculiar variations in abundances relative to the solar *r*-pattern reflecting early contributions from the high-frequency H events (Wasserburg et al. 1996). Evidence in support of this has been found by Sneden et al. (2000), who showed that abundances of heavy *r*-elements from Ba ($A \sim 135$) and above in CS 22892-052 closely follow the solar *r*-pattern, whereas the light *r*-elements around Ag ($A \sim 107$) are somewhat deficient.

Data on Ba and Eu ($A \sim 151$) for UMP stars (McWilliam et al. 1995; McWilliam 1998) show that there is a wide range in Ba/H and Eu/H for a fixed value of [Fe/H] ≈ -3. This suggests that the H events responsible for heavy *r*-nuclei produce very little Fe (Wasserburg & Qian 2000a, hereafter WQ). It was proposed that the (SN II) H events are associated with black hole formation (Qian et al. 1998). This is in accord with the scenario of Brown & Bethe (1994) and could explain the lack of Fe production in these events. The large dispersion in Ba/H and Eu/H at [Fe/H] ≈ -3 was attributed by WQ to the rapid occurrence of high-frequency H events. At [Fe/H] > -2.5 an increasingly clear correlation between abundances of heavy *r*-elements and Fe is observed (e.g., Burris et al. 2000). This correlation would naturally be established as products from both H events and low-frequency Fe-producing L events were mixed in the ISM. The Fe abundance resulting from an L event is $[\mathrm{Fe/H}]_L \approx -2.48$ (WQ).

In addition to H and L events, an initial or prompt (P) inventory of elements is assumed to explain abundances of Fe and other associated elements in stars with [Fe/H] < -3. The P-inventory was attributed to production by the first very massive ($\gtrsim 100\ M_\odot$) stars prior to formation of normal stars ($M \sim 1$–$60\ M_\odot$) and onset of regular SNe II associated with the *r*-process. It was argued that formation of normal stars could not occur until a "metallicity" corresponding to [Fe/H] ≈ -3 was achieved in the ISM (WQ). The P-inventory was considered to represent the earliest stages of chemical evolution that need not be specifically associated with our Galaxy. Data

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TABLE 1

Abundances in the U-Star, *H*-Yields, and *P*-Inventory

Atomic Number (Z)	Element	$\log \epsilon(Z)$	$\log \epsilon_H(Z)$	$\log \epsilon_P(Z)$
38	Sr	0.93	−1.30	0.13
39	Y	0.13	−2.05	−1.05
40	Zr	0.69	−1.53	−0.13
41	Nb	−0.46	−2.61	…
44	Ru	0.54	−1.61	…
45	Rh	−0.26	−2.41	…
46	Pd	0.28	−1.87	…
47	Ag	−0.26	−2.41	…
48	Cd	0.19	−1.96	…
56	Ba	0.63	−1.52	…
57	La	−0.07	−2.22	…
58	Ce	0.13	−2.02	…
59	Pr	−0.36	−2.51	…
60	Nd	0.25	−1.90	…
62	Sm	−0.05	−2.20	…
63	Eu	−0.33	−2.48	…
64	Gd	0.15	−2.00	…
65	Tb	−0.55	−2.70	…
66	Dy	0.23	−1.92	…
67	Ho	−0.38	−2.53	…
68	Er	0.02	−2.13	…
69	Tm	−0.78	−2.93	…
70	Yb	−0.07	−2.22	…
71	Lu	−0.83	−2.98	…
72	Hf	−0.46	−2.61	…
73	Ta	−1.21	−3.36	…
74	W	−0.53	−2.68	…
75	Re	−0.60	−2.75	…
76	Os	0.49	−1.66	…
77	Ir	0.52	−1.63	…
78	Pt	0.81	−1.34	…
79	Au	−0.05	−2.20	…
80	Hg	−0.17	−2.32	…
81	Tl	−0.65	−2.80	…
82	Pb	0.50	−1.65	…
83	Bi	−0.16	−2.31	…
90	^{232}Th	−0.88	−2.72	…
92	^{238}U	−1.72	−2.89	…

Note.—Col. (3): calculated abundances in the U-star; col. (4): *H*-yields; col. (5): prompt inventory (values for $Z > 40$ are negligible). The ^{232}Th and ^{238}U abundances are calculated for an age of 14.5 Gyr.

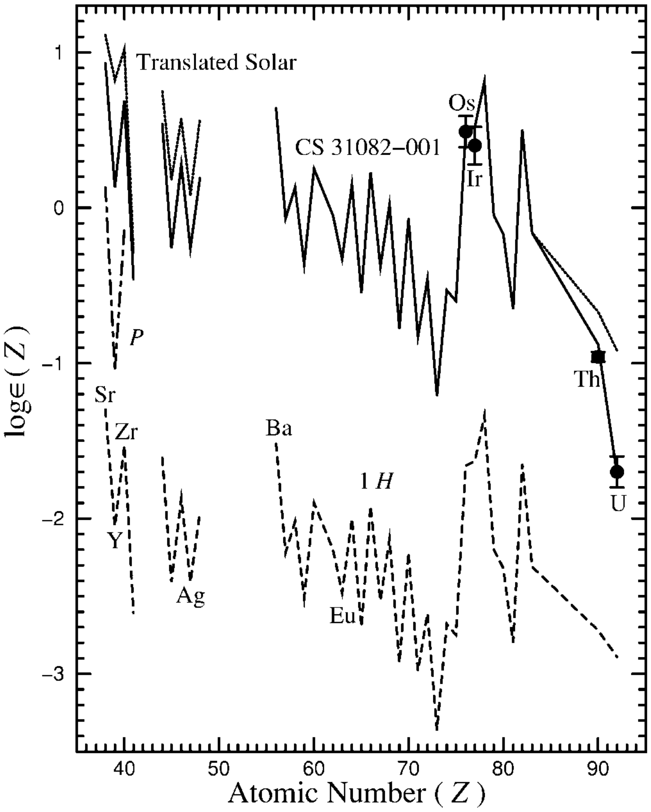

Fig. 1.—The *r*-process yields of an SN II *H* event (*dashed curve*) and the prompt inventory (*dot-dashed curve*) for the three-component model. The solid curve represents the abundances calculated (see Table 1) for the U-star by using the observed Os abundance to determine n_H. The Th and U abundances are calculated for an age of 14.5 Gyr. Filled circles with error bars indicate data from Cayrel et al. (2001). The dotted curve marked "Translated Solar" represents the standard solar *r*-abundances (Käppeler et al. 1989; Arlandini et al. 1999) shifted down to fit the Os data. We note that, based on the data of Burris et al. (2000), QW have given revised solar *r*-abundances for Sr, Zr, and Ba.

on Ba at $-4 \lesssim [\mathrm{Fe/H}] < -3$ (McWilliam et al. 1995; McWilliam 1998; Norris, Ryan, & Beers 2001) indicate that the *P*-inventory of heavy *r*-elements is negligible. As [Fe/H] for UMP stars reflect only the *P*-inventory of Fe ($[\mathrm{Fe/H}]_P \approx -3$) and no *L*-contributions, we consider that abundances of heavy *r*-elements from Ba and above in these stars resulted only from *H* events. Observations by Sneden et al. (1996, 2000) and Westin et al. (2000) show that abundances of these elements in UMP stars very closely follow the solar *r*-pattern. Thus, their *H*-yields can be directly calculated from the solar *r*-abundances. Over the Galactic history of ≈10 Gyr before solar system formation, ≈10^3 *H* events contributed to the solar abundances. The *H*-yield of, e.g., Os ($A \sim 190$) is then $\log \epsilon_H(\mathrm{Os}) \approx \log \epsilon_{\odot,r}(\mathrm{Os}) - 3 = -1.66$, where $\log \epsilon(\mathrm{E}) \equiv \log(\mathrm{E/H}) + 12$ for an element E and $\log \epsilon_{\odot,r}(\mathrm{Os}) = 1.34$ (Käppeler, Beer, & Wisshak 1989; Arlandini et al. 1999) for the solar *r*-inventory of Os. *H*-yields of heavy *r*-elements from Ba and above are given in Table 1.

By comparing the observed abundances of Sr, Y, and Zr with those of the heavy *r*-elements in the UMP stars CS 22892-052 (Sneden et al. 2000) and HD 115444 (Westin et al. 2000), QW found that the Sr, Y, and Zr abundances in these two stars received significant to dominant contributions from a common source, the *P*-inventory. The $\log \epsilon_P$–values for the *P*-inventory of Sr, Y, and Zr and the corresponding *H*-yields (represented by $\log \epsilon_H$) calculated by QW are given in Table 1. The observed Os abundance of $\log \epsilon(\mathrm{Os}) = -0.05$ in CS 22892-052 (Sneden et al. 2000) indicates that this star received contributions from $n_H \approx 41$ *H* events. A slightly different value for n_H is obtained by using the observed Eu abundance as in QW. The *H*-contributions to the Sr, Y, and Zr abundances in CS 22892-052 are larger than the *P*-inventory. We assume that the observed abundances in CS 22892-052 for the light *r*-elements Nb, Ru, Rh, Pd, Ag, and Cd ($A = 93$–116) are dominated by the *H*-contributions. Their *H*-yields are given in Table 1.

H-yields of *r*-elements and the *P*-inventory of Sr, Y, and Zr are shown in Figure 1. As the U-star is a UMP star with no *L*-contributions, *L*-yields calculated by QW are not given. In § 2 we discuss abundances of stable elements in the U-star based on the above three-component model. The abundances of ^{232}Th and ^{238}U in this star and implications for cosmochronology are discussed in § 3.

2. ABUNDANCES OF STABLE ELEMENTS IN THE U-STAR

Data for the U-star clearly show an extremely large enhancement of heavy *r*-elements without any increase in [Fe/H] from the prompt value $[\mathrm{Fe/H}]_P \approx -3$. The observed Os abundance of $\log \epsilon(\mathrm{Os}) = 0.49$ is higher than those in CS 22892-052, HD 115444 ($[\mathrm{Fe/H}] = -2.99$), and HD 122563 ($[\mathrm{Fe/H}] = -2.74$; Sneden et al. 1998) by 0.54, 1.04, and greater than 1.79 dex, respectively. Thus, observations of the U-star clearly confirm the existence of a type of *r*-process event that produces heavy *r*-nuclei but no Fe. This is in support of the hypothesis of the above three-component model that there must be two types of SN II sources for *r*-nuclei, one of which does not produce Fe.

Using $\log \epsilon_H(\mathrm{Os}) = -1.66$, we obtain from the observed Os abundance in the U-star that it had received contributions from $n_H \approx 141$ H events. The abundances of all other stable *r*-elements can be calculated from n_H and the H-yields and the P-inventory in Table 1. These calculated abundances are given in Table 1 and shown in Figure 1. While Sr, Y, and Zr have substantial contributions from the P-inventory, these are small compared with the contributions from ≈41 H events for CS 22892-052 or those from ≈141 H events for the U-star. Figure 1 also shows the solar *r*-pattern translated to fit the observed Os abundance in the U-star. The calculated abundances for the U-star show that it should be deficient in the light *r*-elements from Sr to below Ba (particularly Y) relative to the solar *r*-pattern. Assuming the validity of the model, we consider the abundances predicted here for the U-star to be quantitative and reasonably reliable subject to uncertainties in the observational data from which the H-yields and the P-inventory are derived. Absolute abundances relative to hydrogen in this star will provide a direct and rigorous test of the approach laid out here. We were informed by the referee that these are under active study (Hill et al. 2001). The essential conclusion from our results is that abundances in the U-star should reflect the relative yield pattern of an H event in addition to simply exhibiting high *r*-process enrichments.

The high numbers of H events for CS 22892-052 and the U-star require discussion. These two UMP stars have essentially the same [Fe/H] as the prompt value $[\mathrm{Fe/H}]_P \approx -3$. Thus, they cannot have received contributions from any Fe-producing L events. From the frequencies of H and L events in an average ISM, the average fraction of H events among all SNe II is $q \approx 0.9$. The probability for a standard reference mass of ISM to have a number n_H of H events in a series is q^{n_H}. The number $n_H \approx 41$ for CS 22892-052 corresponds to a small probability of $\approx 1.3 \times 10^{-2}$ and the number $n_H \approx 141$ for the U-star to an extremely low probability of $\approx 3.5 \times 10^{-7}$. It follows that the observed high enrichment of *r*-elements in the U-star and possibly also CS 22892-052 cannot be plausibly associated with many H events randomly contaminating the ISM but requires a special source.

It takes $\approx 10^3$ H events over ≈10 Gyr to produce the solar *r*-process ratio $(\mathrm{Os/H})_{\odot,r}$ in a standard reference mass of ISM. For the present Galactic SN II rate of $\approx(30\ \mathrm{yr})^{-1}$ corresponding to a total gas mass of $\approx 10^{10}\ M_\odot$, the standard reference mass is $\approx 3 \times 10^4\ M_\odot$. This is in accord with the typical mass of ISM swept by an SN II remnant (e.g., Thornton et al. 1998). To explain the observed Os abundance in the U-star by a special H event contaminating the ISM would require either extremely large fluctuations in the *r*-process production by an H event or wide variations in the amount of ISM that dilutes the *r*-process ejecta. It follows that the abundances in the U-star do not represent a sample of the ISM with enormous enhancement in *r*-elements. We propose that the U-star was once a binary companion to a massive (~ 10–$60\ M_\odot$) star. The massive star exploded as an SN II H event and contaminated the U-star, providing a high enhancement in its surface abundances of *r*-elements. If the *r*-process material received from the SN II is mixed with $\sim 10^{-2}\ M_\odot$ of hydrogen in the surface layer of the U-star, then only a fraction $\sim 141(10^{-2}/3 \times 10^4) \approx 5 \times 10^{-5}$ of the *r*-process ejecta from an H event is needed to give the observed enhancement of *r*-elements in this star. If the proposed binary survived the SN II explosion, the U-star should now have a compact companion, most likely a stellar-mass black hole. We were informed that the U-star has a rather high proper motion for its distance. Long-term observations of its radial velocity should provide a definitive test of whether it is in a binary. We note that a large overabundance of O, Mg, Si, and S associated with SN II explosions has been observed in the binary companion to a possible black hole (Israelian et al. 1999).

We have ignored the possibility that neutron star mergers (NSMs) could be responsible for the heavy *r*-elements. If NSMs were the source for such elements in the Sun, the average enrichment resulting from an NSM would be $\sim 3 \times 10^3$ times that for an SN II H event (Qian 2000). To explain the observed Os abundance in the U-star and the range of Os abundances in other UMP stars [a scatter in $\log \epsilon(\mathrm{Os})$ of greater than 1.79 dex] by NSMs would then require grossly variable amounts of ISM to mix with the ejecta. As NSMs play essentially no role in Fe enrichment, the large scatter in abundances of heavy *r*-elements should persist at $[\mathrm{Fe/H}] > -3$ if NSMs were the sources for these elements (Qian 2000). However, the extensive data of Burris et al. (2000) on the heavy *r*-element Eu show that the scatter in $\log \epsilon(\mathrm{Eu})$ is ≈1 dex at $[\mathrm{Fe/H}] \approx -2.5$ and decreases at higher [Fe/H]. Thus, we do not consider that NSMs are the source for the heavy *r*-elements, nor can they explain the observed *r*-abundances in the U-star.

3. ^{232}Th AND ^{238}U ABUNDANCES IN THE U-STAR AND COSMOCHRONOLOGY

Abundances of ^{232}Th and ^{238}U in the U-star have been used to determine the age of this star (Cayrel et al. 2001). If the ^{232}Th and ^{238}U observed in a star are the result of a single SN II H event, the age equation for the star is

$$\left(\frac{^{238}\mathrm{U}}{^{232}\mathrm{Th}}\right) = \left(\frac{Y_{238}}{Y_{232}}\right) \exp\left[-\left(\frac{t_{\mathrm{star}}}{\bar{\tau}_{238}} - \frac{t_{\mathrm{star}}}{\bar{\tau}_{232}}\right)\right], \tag{1}$$

where Y_{238}/Y_{232} is the relative yield of ^{238}U to ^{232}Th for the H event, $\bar{\tau}_{238} = 6.45$ Gyr and $\bar{\tau}_{232} = 20.3$ Gyr are the lifetimes of the two nuclei, and t_{star} is the time interval between the event and observation. As emphasized by Cowan et al. (1999) and Goriely & Clerbaux (1999), the calculated age depends critically on the relative yields that are very difficult to determine from ab initio *r*-process models. The solar inventory of *r*-nuclei at the time of solar system formation (SSF; 4.55 Gyr before the present time) is the result of previous Galactic nucleosynthesis. Assuming that the rate of SN II production per hydrogen atom in the ISM is constant, we have

$$\left(\frac{^{238}\mathrm{U}}{^{232}\mathrm{Th}}\right)_{\odot}^{\mathrm{SSF}} = \left(\frac{Y_{238}}{Y_{232}}\right) \left[\left(\frac{\bar{\tau}_{238}}{\bar{\tau}_{232}}\right) \frac{1 - \exp(-T_{\mathrm{UP}}/\bar{\tau}_{238})}{1 - \exp(-T_{\mathrm{UP}}/\bar{\tau}_{232})}\right], \tag{2}$$

where T_{UP} is the total time of uniform *r*-process production prior to SSF. The ratio $(^{238}\mathrm{U}/^{232}\mathrm{Th})_{\odot}^{\mathrm{SSF}} = 0.431$ (Anders & Grevesse 1989) has an uncertainty of less than 10%. The term in square brackets in equation (2) ranges from 1 (for $T_{\mathrm{UP}} = 0$) to 0.318 ($T_{\mathrm{UP}} = \infty$). Thus, there is only an extremely restricted range in Y_{238}/Y_{232} for a wide range in T_{UP}. The relationship between timescales and long-lived and short-lived *r*-nuclei has been discussed extensively by Schramm & Wasserburg (1970). An estimate of Y_{238}/Y_{232} was first made by Burbidge et al. (1957) and later by

Fowler & Hoyle (1960) based on the number of progenitors for ^{232}Th and ^{238}U. The estimated value of $Y_{238}/Y_{232} \approx 0.61 \pm 0.06$ with guesstimated errors has not been substantially improved upon over the past 40 years (cf. Cowan et al. 1999; Goriely & Clerbaux 1999). For these values of Y_{238}/Y_{232} we obtain $T_{\rm UP} \approx 7.5 \pm 2.5$ Gyr, which corresponds to a time of ≈12 ± 2.5 Gyr since the onset of Galactic *r*-process nucleosynthesis. The age of 12.5 ± 3 Gyr for the U-star obtained by Cayrel et al. (2001) is for a single event. The value $Y_{238}/Y_{232} \approx 0.61$ corresponds to an age of ≈11.4 Gyr for this star. The estimated ages of the U-star, the values of $T_{\rm UP}$ calculated from the solar system data for uniform *r*-process production rates, and the timescale calculated by Fowler & Hoyle (1960) for an exponential model are in general accord.

The values of $T_{\rm UP}$ are also consistent with the uniform production period assumed above to calculate the number of SN II *H* events contributing to the solar inventory. The *H*-yield of ^{232}Th can be calculated from

$$\left(\frac{^{232}\mathrm{Th}}{\mathrm{H}}\right)^{\rm SSF}_{\odot} = \left(\frac{^{232}\mathrm{Th}}{\mathrm{H}}\right)_H f_H \bar{\tau}_{232}\left[1 - \exp\left(-\frac{T_{\rm UP}}{\bar{\tau}_{232}}\right)\right], \quad (3)$$

where $f_H \approx (10^7\ \mathrm{yr})^{-1}$ is the frequency of *H* events. For $T_{\rm UP} \approx 10$ Gyr we obtain $\log \epsilon_H(^{232}\mathrm{Th}) \approx -2.72$. A value of $\log \epsilon_H(^{238}\mathrm{U}) \approx -2.89$ is similarly obtained. These yields are consistent with the observed Th and U abundances in the U-star for an age of 14.5 Gyr (see Fig. 1).

A deeper question is the relationship of ages obtained from *r*-process chronometers to the age of the universe. It has been argued above that onset of *r*-process nucleosynthesis was represented by rapid occurrence of *H* events at [Fe/H] ≈ −3. These events were preceded by nucleosynthesis in the first very massive stars that significantly produced only elements up to Zr. The timescale over which aggregation of matter proceeded until a metallicity corresponding to [Fe/H] ≈ −3 was achieved to permit formation of normal stars is not established. In addition, assembly, disassembly, and reassembly of baryonic matter at various stages in earlier epochs of the universe possibly leave a large time interval prior to onset of SNe II. From consideration of [Fe/H] in damped Lyα systems, it has been argued that there is a long interval (∼1–5 Gyr) between the big bang and onset of normal star formation in protogalaxies (Wasserburg & Qian 2000b). Thus, the ages obtained from *r*-process chronometers are substantially less than the age of the universe.

We would like to dedicate this Letter to Willy Fowler and Fred Hoyle, who might at some time have enjoyed and engaged in these efforts. Support, interest, and provocation by Roger Blandford are greatly appreciated. We thank Tim Beers for a thorough, insightful, and prompt review. We acknowledge Kris Davidson and Roberta Humphreys for information on the proper motion of the U-star. This work was supported in part by DOE grants DE-FG02-87ER40328 and DE-FG02-00ER41149 (Y.-Z. Q.) and by NASA grant NAG5-4083 (G. J. W.), Caltech Division Contribution 8764(1075).

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