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10. This does not mean that these trends originate through the mixing of only two components. We believe that the linear trends record binary-like mixing between a volume of mantle with composition C and another mantle volume of distinct isotope composition that can be described by reference to the external components. We use the notion of mantle components as reference coordinates in isotope space. The isotopic composition of any particular volume of mantle is actually the product of a unique sequence of geological processes, not simply the mixing of the DM, EM, and HIMU components.
11. The MORB and OIB databases clearly show the tendency for oceanic basalt data to focus on the internal component C (*2–4*). However, not all individual OIB and MORB data suites converge on C. For example, in the equatorial Atlantic, local mixing vectors in Pb/Pb isotope space extend beyond C with $^{206}Pb/^{204}Pb > 20$ as a result of hot spot–ridge interaction between the MORB mantle beneath the ridge at 1.7°N and the Sierra Leone plume (*29*). The Sierra Leone plume can be viewed as a multicomponent mixture of C-like, HIMU-like, and local depleted mantle. Other examples of hot spot–ridge interactions that show similar complexity include the Reykjanes Ridge (*30*), the southern Mid-Atlantic Ridge (*5*), and Galápagos spreading center (*31*). We view plumes as consisting of both C material and other materials of variable compositions that can be described as multicomponent mixtures of the external components DM, EM1, EM2, and HIMU, with a multistage history of mixing (*10*).
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19. C and PHEM have similar intermediate $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios, approximately 0.7035 versus 0.7047 and 0.51290 versus 0.51273 [$\varepsilon_{Nd}$ (*9*) of 5.0 versus 1.8], respectively (*4, 5*). In contrast, FOZO originally was estimated to have depleted $^{87}Sr/^{86}Sr$ ratios and $^{143}Nd/^{144}Nd$ isotope signatures of about 0.7025 and 0.51314 ($\varepsilon_{Nd} = 10$), respectively (*2*), but these have been modified to $^{87}Sr/^{86}Sr = 0.7035$ and $^{143}Nd/^{144}Nd = 0.5129$ (*3*).
20. We use the 4.57-Ga reference geochron determined from meteorites (*32*) as a reference to discuss the Pb isotope composition for the bulk Earth and mass balance for Earth's Pb reservoirs in the $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ diagram. Meteorites and Earth are assumed to have a common age and to have initially had the same Pb isotope composition because meteorites and average modern terrestrial Pb fall on the same Pb/Pb isochron, the 4.57-Ga geochron. This geochron is the locus of all Earth reservoirs that have evolved from Earth's starting Pb isotope composition, but with different U/Pb ratios. Because most mantle and crustal rocks plot below the geochron and because the bulk Earth must lie on it, either an unknown reservoir plotting above the 4.57-Ga geochron or a younger age for Earth's Pb, moving the geochron down, is required to achieve mass balance.
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# Pre–Main-Sequence Star Candidates in the Bar of the Large Magellanic Cloud

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Candidate pre–main-sequence stars were observed in the bar of the Large Magellanic Cloud during the search for dark matter in the galactic halo. Seven blue stars of apparent visual magnitude 15 to 17 had irregular photometric variations and hydrogen emission lines in their optical spectra, which suggested that these stars are pre–main-sequence stars of about 10 solar masses. These stars are slightly more massive and definitely more luminous than are Herbig AeBe pre–main-sequence stars in our own galaxy. Continued observations of these very young stars from another galaxy, which are probably at the pre–hydrogen-burning stage, should provide important clues about early stages of star formation.

The early stages of star formation are generally hidden from optical observations because the stars are embedded in their circumstellar dust clouds. The lower the mass of a star, the slower its contraction toward the main sequence where H is ignited. Therefore, the only pre–main-sequence stars that are optically visible in the galaxy are the low-mass T Tauri stars ($M \simeq 1$ to $5\ M_{\odot}$, where $M_{\odot}$ is solar mass) and the slightly more massive Herbig AeBe (HAeBe) stars of 2 to 9 $M_{\odot}$. In galaxies with a lower metallicity, the pre–main-sequence stars are expected to have less dust. This attribute might enable us to observe and study the pre–main-sequence phase of more massive stars in other galaxies, thereby extending our knowledge of the early evolution of stars to younger phases. Here, we report the serendipitous discovery of HAeBe stars in the Large Magellanic Cloud (LMC) with the EROS experiment (*1*).

The EROS database was used to search for quasi-stellar objects (QSOs) behind the LMC for spectroscopic studies of the absorption components of gas in the LMC. About 10 to 12 QSOs down to magnitude ~20 were expected in the field of the EROS charge-coupled device (CCD) camera. Because the EROS photometry has only two filters and it is impossible to select QSOs on the basis of two-color photometry, we decided to search for QSOs on the basis of their light curves. We expected about two or three QSOs with irregular brightness variations in the EROS data set. Seven objects were identified on the basis of three criteria: (i) $B_E - R_E < 0.5$ magnitudes (*1*), to exclude the red irregularly variable stars; (ii) photometric variability larger than twice the standard deviation; and (iii) either a nonperiodic light curve, or a periodic light curve whose most probable period was greater than half the duration of the observing campaign. Subsequent spectroscopic observations showed that all seven objects were stars in the LMC; the stars were consequently named EROS LMC HAeBe candidates (ELHCs). All the objects showed irregular amplitude variations of about 0.2 to 0.6 $B_E$ magnitudes in their light curves (Fig. 1). Most of the stars showed variability on a time scale of ~10 days superimposed on slower variations, except for ELHC7, which had a very pronounced dip in its light curve with a time scale of ~30 days. On the basis of the light curve alone, the stars cannot easily be classified or grouped into the same class of objects.

Six of the stars are relatively bright, with mean $B_E$ and $R_E$ magnitudes between 14.7 and 15.8 (Table 1). These magnitudes correspond to apparent visual magnitude $V \simeq 14.8$ to 15.8. Assuming a typical interstellar galactic foreground extinction of $A_V \simeq 0.2$ plus a mean extinction of $A_V \simeq 0.30$ for the bar of the LMC and a distance modulus of 18.50 for the LMC, we conclude that the absolute visual magnitudes $M_V$ of the stars (except ELHC7) are in the range $M_V \simeq -3.2$ to $-4.3$. This range excludes a classification as cataclysmic variables because such variables would have been several magnitudes fainter. The mean $B - V$ (blue light minus visible light) color of the stars is between −0.01 and 0.10. Correcting for the mean reddening $E(B - V) \simeq 0.17$ of the LMC stars, we find intrinsic colors of $(B - V)_0 \simeq -0.18$ to $-0.07$. These are typical values for stars of spectral types B3 to B9. Combining these colors with the values of $M_V$, we conclude that the objects are B-type stars with luminosity classes of about II to III.

The luminosities $L$ of the six stars, derived from $M_V$ with the bolometric corrections adopted from the intrinsic colors (*2*), are log $L/L_\odot \simeq 3.5$ to 3.9 (Table 1). In this estimate, we have assumed that the stars have no circumstellar (CS) extinction. If there is circumstellar extinction, the intrinsic colors will be bluer, the spectral types earlier, and the luminosity larger. The CS extinction cannot be very large because the minimum allowed value of $(B - V)_0$ is −0.32. We also calculated the magnitudes and colors for an assumed additional extinction of $E(B - V)_{CS} = 0.15$. In this case, the luminosities are in the range log $L/L_\odot \simeq 4.2$ to 4.8 (except ELHC7). The variable ELHC stars are probably abnormal B-type giants similar to galactic HAeBe stars because they have irregular photometric variables (*3*).

The possibility that the ELHC stars are LMC counterparts of the galactic pre–main-sequence HAeBe stars is supported by the optical spectra. Low-resolution spectra of the ELHC stars in the wavelength range of 3600 Å < λ < 7000 Å were obtained in August 1994 at the European Southern Observatory 1.5-m and 3.6-m telescopes equipped with Boller and Chiven spectrographs (*4*). All the targets have a stellar-type spectrum with a very strong Hα emission line and strong photospheric Balmer absorption lines; hence, the targets are stars, not QSOs. The stellar radial velocity derived from the Balmer absorption lines is 270 km $s^{-1}$, which proves that the stars belong to the LMC. We estimated the spectral type for each star on the basis of the presence or absence of classification lines. However, because the metallicity of the LMC stars is about one-half that in our galaxy, several of the classification lines are weaker. Therefore, the classification as B-type stars from the spectra agrees roughly with a similar classification on the basis of the colors of the stars.

We suggest that our program stars are pre–main-sequence stars, similar to the galactic HAeBe stars. This suggestion is supported by the following arguments:

1) All the stars have Hα emission lines with equivalent width in the range 11 to 130 Å, quite similar to the range of 8 to 126 Å for the galactic HAeBe stars (*5*). Normal Be stars have smaller Hα equivalent widths and do not show the rapid, irregular photometric variations of our stars.

2) The colors and the presence of the strong photospheric Balmer absorption lines and He I absorption lines in some stars suggest spectral types between late B (for stars without strong He I lines) and mid- to early B (for stars with He I lines).

3) The spectra of several of our stars show evidence for Balmer continuum emission, possibly as a result of circumstellar gas that is optically thick in the Balmer continuum, which indicates the presence of an accretion disk or an optically thick wind (*6*).

4) The ELHC stars have irregular photometric variables. Irregular photometric variability is characteristic of HAeBe stars. The

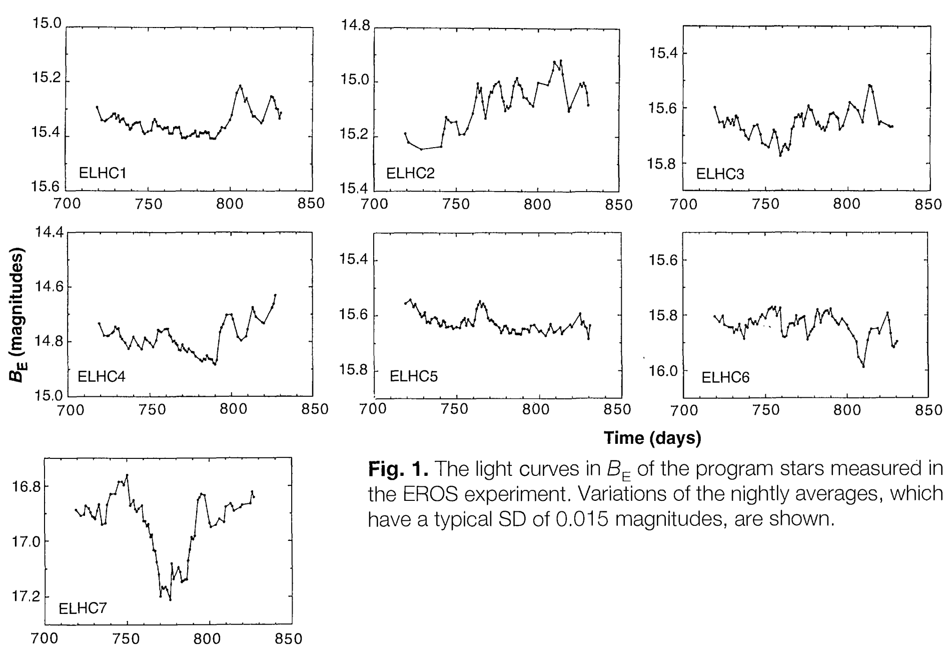


**Fig. 1.** The light curves in $B_E$ of the program stars measured in the EROS experiment. Variations of the nightly averages, which have a typical SD of 0.015 magnitudes, are shown.

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**Table 1.** Photometry and approximate spectral types. Two extreme estimates of circumstellar reddening, which define a possible range of luminosity and effective temperature $T_{eff}$ (in kelvin), are given for each star.

| Star | α (J2000) δ (J2000) | $B_E$ | $R_E$ | $B - V$ | $(B - V)_0$ | $M_V$ | Log $L/L_\odot$ (derived from $M_V$) | Type color | Log $T_{eff}$ | Log $L/L_\odot$ (assuming CS extinction) | Hα (Å) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ELHC1 | 5 18 15.3 | 15.35 | 15.30 | 0.05 | −0.12 | −3.7 | 3.8 | B7 | 4.25 ± 0.13 | 4.2 ± 0.4 | 30 |
| | −69 30 15 | | | | −0.27 | −4.1 | 4.5 | B1 | | | |
| ELHC2 | 5 18 33.6 | 15.10 | 15.10 | 0.02 | −0.15 | −4.0 | 3.9 | B6 | 4.30 ± 0.16 | 4.2 ± 0.3 | 104 |
| | −69 39 42 | | | | −0.30 | −4.4 | 4.4 | B0 | | | |
| ELHC3 | 5 16 29.5 | 15.66 | 15.67 | −0.01 | −0.18 | −3.4 | 3.8 | B3 | 4.40 ± 0.17 | 4.2 ± 0.4 | 15 |
| | −69 17 17 | | | | −0.33 | −3.8 | 4.6 | O7 | | | |
| ELHC4 | 5 17 18.3 | 14.78 | 14.70 | 0.07 | −0.10 | −4.3 | 3.9 | B8 | 4.24 ± 0.14 | 4.3 ± 0.4 | 16 |
| | −69 21 38 | | | | −0.25 | −4.7 | 4.7 | B1 | | | |
| ELHC5 | 5 18 21.3 | 15.63 | 15.64 | −0.01 | −0.18 | −3.4 | 3.8 | B3 | 4.40 ± 0.17 | 4.2 ± 0.4 | 11 |
| | −69 32 39 | | | | −0.33 | −3.8 | 4.6 | O7 | | | |
| ELHC6 | 5 18 18.7 | 15.84 | 15.73 | 0.10 | −0.07 | −3.2 | 3.5 | B9 | 4.17 ± 0.15 | 3.9 ± 0.4 | 20 |
| | −69 35 30 | | | | −0.22 | −3.7 | 4.2 | B2 | | | |
| ELHC7 | 5 16 39.5 | 16.94 | 16.88 | 0.06 | −0.11 | −2.1 | 3.1 | B8 | 4.24 ± 0.14 | 3.5 ± 0.4 | 130 |
| | −69 20 49 | | | | −0.26 | −2.5 | 3.9 | B1 | | | |

galactic HAeBe stars of early spectral type exhibit small brightness variations ($\Delta V \sim 0.1$) with a time scale of 20 to 60 days and with no evidence for clear periodicities, as well as large brightness changes that are completely irregular and unpredictable. The time scale of about 10 to 40 days for photometric variations of our program stars is similar.

5) The most important characteristic of the galactic HAeBe stars is their association with nebulosities and their location in star-forming regions. Unfortunately, we do not know if our stars are in star-forming regions in the bar of the LMC. However, the two-dimensional optical spectra of our stars show that all of them (except ELHC1, for which the resolution and signal/noise ratio are too low) are located in H II regions. This finding indicates that our stars are associated with O stars, that is, with young regions where star formation might occur.

The ELHC stars are up to 10 times as luminous as the galactic HAeBe stars in the same temperature range (Fig. 2). The luminosity of the stars suggests that they are pre–main-sequence stars with masses between 7 and 12 $M_\odot$ if $E(B - V) = 0.17$, or between 12 and 25 $M_\odot$ if $E(B - V) = 0.32$. These masses are greater than those of the galactic HAeBe stars, which are typically in the range of 2 to 9 $M_\odot$.

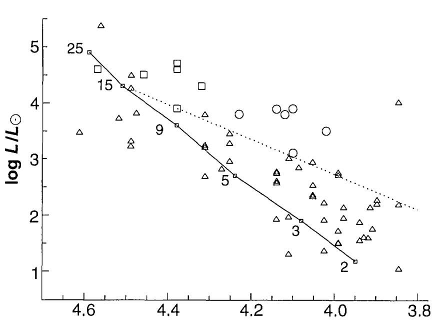


**Fig. 2.** Locations of the ELHC stars in the Hertzsprung-Russel diagram. The ELHC stars are indicated by two positions: the circles and squares correspond to the minimum value of $E(B - V) = 0.17$ and to $E(B - V) = 0.32$, respectively. The locations of the galactic HAeBe stars (*8*) are indicated by triangles. The dotted line is the upper limit of the HAeBe stars, with the exception of two luminous hot and cool stars. The solid line is the main sequence, shown along with masses.

The observed upper limit for the galactic HAeBe stars corresponds approximately to the location of the galactic birth line (*8*) for an accretion rate of $10^{-5}$ $M_\odot$ year$^{-1}$. This line gives the location of the pre–main-sequence stars in the Hertzsprung-Russel diagram when they become optically visible through their surrounding dust clouds. For stars more luminous than about $2 \times 10^3$ $L_\odot$, the birth line coincides with the main sequence. Thus, pre–main-sequence stars of $M > 9$ $M_\odot$ are not expected to be optically visible before they reach central H ignition on the main sequence. The ELHC stars are clearly above the galactic birth line, which might be partly attributable to a selection effect of the brightest variable stars in the LMC. However, of the many galactic HAeBe stars studied, at most one of them reaches the brightness of the ELHC stars in the same temperature range.

We propose three possible explanations for the dissimilar luminosities of the ELHC stars:

1) The low metallicity of the LMC stars results in a smaller amount of dust around contracting stars than in our galaxy. As a result, LMC pre–main-sequence stars will become optically visible in an earlier phase of their contraction than will their galactic counterparts.

2) The accretion rate of the pre–main-sequence stars in the LMC may be higher than for galactic stars of the same luminosity, possibly because the radiation pressure in circumstellar matter of low metallicity is smaller than for galactic stars. This effect will shift the birth line to greater luminosity.

3) An accretion disk, an associated nebula, or both might contribute a non-negligible fraction to the luminosity of the ELHC stars.

## REFERENCES AND NOTES


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4. The velocity resolution is between 150 and 230 km s$^{-1}$, and the absolute wavelength calibration has a precision better than $\Delta v$ = 14 to 28 km s$^{-1}$. The flux calibration has a precision of ~5% near Hα and ~10% near 4000 Å. The signal/noise ratio of the spectra is between 15 (for ELHC7) and 75 (for ELHC5 and ELHC6).
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