The 9 Aurigae System*

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Abstract

The F0 V star 9 Aur A exhibits an irregular variability of amplitude \( \approx 0.1 \) magnitude at optical wavelengths. The variations are too slow for it to be a \( \delta \) Scuti-type star. There is no evidence for a close, interacting companion or ring of dust, either from infrared, ultraviolet, or speckle data. The photometric variability of 9 Aur A is similar to two other early F dwarf stars: \( \gamma \) Doradus and HD 96008. 9 Aur B appears to be an M dwarf, 9 Aur C is an early- to mid-K dwarf star, and 9 Aur E, if it is a member of the system, probably is a normal white dwarf. 9 Aur D is most likely an unrelated and distant K giant.

Key words: Stars, double and multiple - Photometry, 9 Aur - Stars, variable

1. Introduction

9 Aurigae (= BS 1637 = HD 32537 = \( \beta \) 1046 = SAO 25019 = Gliese 187.2 = ADS 3675 = IRAS 0527+5131) is a multiple star system whose V \( \approx 5.0 \) magnitude primary is of spectral type F0 V. The distance modulus of the primary is \( m - M = 1.55 \pm 0.6 \) (probable error), adopting Gliese's (1969) parallax of \( 0.049 \pm 0.013 \) (p.e.) arcsec. Wagman (1967) found a parallax of \( 0.057 \pm 0.005 \) (p.e.) arcsec.

Krisciunas & Guinan (1990) found 9 Aur A to be variable at optical wavelengths by about 0.1 magnitude. Guinan's data, from 52 nights of observations at Mt. Hopkins using an automatic photoelectric telescope (APT) from 1989 November to 1990 March, indicated a range of V = 4.96 to 5.07.
Photometry from 1987 January to 1990 April indicated a period of about 36-39 days (Krisiunas & Guinan 1990). However, subsequent photometry (Krisiunas et al. 1991), while exhibiting a similar range of brightness, did not bear out the previously observed periodicity (see Fig. 1).

Given its position in the Hertzsprung-Russell Diagram, 9 Aur should not be variable. It lies outside the cool edge of the instability strip (Breger 1979), so it should not pulsate. Its light curve from 1987 to 1990 was not indicative of an eclipsing binary.

This paper investigates possible causes of the variability in 9 Aur A and proposes rough classifications for the other fainter components of the 9 Aur system.

2. Variability of the Primary: Possible Causes and Recent Observations

2.1 A close companion?

Abt (1965) initially reported that 9 Aur A is a spectroscopic binary with an orbital period of 391.7 days. However, subsequently Abt & Levy (1974) “could not confirm the previous orbit” and concluded that its radial velocity was constant, i.e. that the primary had no close companion. Hartkopf & McAlister (1984) have made speckle observations of 9 Aur A in order to search for a close stellar companion. They found nothing to a limit in angular separation of 0.03 arcsec, but would have been unable to detect a close companion if it were more than 2.5 magnitudes fainter than the primary (Worley 1992, private communication).

A companion which is considerably hotter or cooler than the primary could be detected by infrared or ultraviolet observations. Near infrared pho-
tometry obtained by Geballe and Aspin, using the United Kingdom Infrared Telescope, is combined with optical photometry (Hoffleit & Jaschek 1982) in Fig. 2. The data are well fitted by a single Planck function with $T = 7179$ K. Simon (1992, private communication) has obtained an IUE (1100-2200 Å spectrum of 9 Aur, finding no evidence for a close, hot companion. Thus, on the basis of infrared, ultraviolet, and speckle data, there is no evidence for a close companion of 9 Aur A.

2.2 Circumstellar material?

Could eclipses of 9 Aur A caused by a lumpy ring of dust around the star be responsible for its variability? To do so and be consistent with the observed variability, one might expect the ring to have a rotational period of $\approx 40$ days. Given Kepler’s Third Law and the temperature and mass of the F0 V primary (1.38 $M_{\odot}$ (Takeda 1984) to 1.7 $M_{\odot}$ (Allen 1973, p. 209)), such a ring of dust would be heated to $\approx 800$ K and would produce an infrared excess at 3-4 microns. This is ruled out by the new infrared photometric data.

9 Aur was detected by IRAS at 12 microns, but not at 25, 60, or 100 microns. The 12 micron flux given in the IRAS catalogue (1988) is 0.95 Jy, with an uncertainty of $\approx 0.08$ Jy. The position angle of the 0.76 by 4.6 arcmin beam (Fullmer & Lonsdale 1989) was 81 deg; thus the B component ($r \approx 5$ arcsec, position angle $\approx 82$ deg), the C component ($r = 90$ arcsec, $PA = 61$ deg), and possibly the D component would have been included in the IRAS beam. Assuming that the B component is an M2 dwarf and that the C component is a K5 dwarf (see below), the 12 micron fluxes of the A, B, and C components are $\approx 0.67$, 0.02, and 0.10 Jy, respectively. The contribution
from the D component is expected to be negligible (see below). The sum of these fluxes, 0.79 Jy, is marginally significantly less than the measured IRAS flux. Thus, there is little evidence of a significant infrared excess in 9 Aur system and it seems unlikely that variable obscuration could be the cause of the variability of the primary.

2.3 Rotational modulation of surface features?

Recently, Abt obtained a reliable value of $v \sin i = 20$ km/sec for 9 Aur (see Krisciunas et al. 1991). (The value of 14 km/sec in The Bright Star Catalogue (Hoffleit & Jaschek 1982) is probably based on Huang (1953) and is not definitive.) Takeda (1984) gives a radius of $1.95 \pm 0.50 R_\odot$ for the star, based on its position in the HR Diagram. This would indicate a rotational period of $4.93 \pm 1.26$ days times $\sin i$. Thus the optical variability observed from 1987 to 1990 cannot be attributed to a rotational effect. One possibility is that we are observing 9 Aur A roughly pole-on, and rotational modulation of bright or dark spots would be seen only if such surface features were near the star’s equator. Otherwise, the observed variability would be on time scales corresponding to the growth and decay of the surface features.

2.4 Pulsations?

Taking the reported radial velocities at face value (Abt & Levy 1974; Takeda 1984; Duquennoy et al. 1991), it is conceivable that the radial velocity of 9 Aur varies from -2.1 to +3.5 km/sec. If 9 Aur were a $\delta$ Scuti star, its principal period of pulsation would be some tens of minutes. Krisciunas et al. (1991) sought evidence for short term pulsations of 9 Aur, based on photometry lasting up to 5.6 hours per night and radial velocity measurements (on one occasion 28 radial velocities were obtained over a span of 2 hours).
No evidence of pulsations was found from the photometry or radial velocities. From December 1990 to March 1991 the observed range of brightness was $V = 4.93$ to 5.00 from the nightly means, but real, shorter term variations were observed on several individual nights (see Fig. 3), which were linear changes of brightness of about 0.01 mag/hr. Skillman’s data of 1991 February 1-17 UT, which are contained in IAU File 238 of Unpublished Observations of Variable Stars (see Breger et al. 1990), indicate possible periods of 0.54 and 1.37 days, but these may just be artifacts of aliasing. If such periods exist, they could only be substantiated by data taken over several days by telescopes distributed around the Earth in longitude.

2.5 Recent photometry

A recent optical campaign by observers situated from the eastern United States to Japan was carried out in 1992 from January 31 to February 10 UT. Altogether 237 useful differential V-band observations were obtained of 9 Aur vs. BS 1561. Table I lists the parameters of the observations including the number of differential measures of 9 Aur and the typical internal error of individual differential measures (primarily from 120 observations of BS 1568 vs. BS 1561). Figure 4 displays the nightly means during the observing period. The complete data set can be found in IAU File 244 (see Breger et al. 1990). From the nightly means the observations show variations of up to 0.057 mag. There is no evidence in these data for the previously reported 36-39 day variations or for linear variations of 0.01 mag/hour.

To search for periodicities the above data were analyzed by means of the Lomb-Scargle algorithm (see Press & Teukolsky 1988). We used an oversampling factor of 4. Figure 5 shows the V-band power spectrum up to
frequencies of half the Nyquist frequency. No significant peaks are to be found from 0.5 to 2.0 times the Nyquist frequency. The highest peak of the resultant power spectrum corresponds to a period of 2.725 days, with a false alarm probability of $10^{-20}$. In Fig. 6 we show the data folded by a period corresponding to the most significant peak in the power spectrum. Other peaks show up in the power spectrum, such as a 1.277 day peak with a false alarm probability of $10^{-18}$. Peaks near 1, 2, and 3 cycles/day may be artifacts of aliasing, since we did not have round-the-clock coverage.

Frequency analysis of the check star (BS 1568) vs. BS 1561 data gave no significant peaks in the power spectrum corresponding to the just-mentioned periods, and no peaks with false alarm probabilities less than about 0.03. This is further evidence that both the comparison star and check star are constant, and that 9 Aur is a bona fide variable.

Because of the large scatter of data on a given night for a given observer compared to the variations of the nightly means, we do not place much trust in the permanence of the peaks in the power spectrum. Still, the data provide evidence that variations are taking place on short time scales, suggesting rotational modulation of surface spots as a possible cause. If 2.725 days were the true rotational period of 9 Aur A, equating it to the period derived from the rotational velocity (see §2.3) implies an inclination angle of $\approx 34\,\text{deg}$.

2.6 Colors, Abundances

Photometry given by Eggen (1963), Hoffleit & Jaschek (1982), and obtained by us indicate that 9 Aur A has a B-V color in the range 0.30-0.35. Its measured U-B color ranges between +0.017 and -0.04, and perhaps as low as -0.13. (We do not imply that the colors are variable - just that different
observers obtained data that are systematically different.) According to the
data in Hoffleit & Jaschek, F0 V stars have \( <B-V> = 0.28 \) and \( <U-B> = +0.07 \). Thus, 9 Aur A has a B-V color several hundredths of a magnitude redder than the “average” F0 dwarf star, and an apparent UV excess of 0.05-0.11 (and perhaps 0.20) mag. If this \( \approx 0.1 \) mag excess were attributed an underabundance of metals, the implied \([Fe/H]\) would be approximately -0.4 (Carney 1979). However, 9 Aur A has essentially solar abundances. Provost & van’t Veer-Menneret (1969), Bell (1971), and Cayrel de Strobel et al. (1980) give \([Fe/H] = +0.01, +0.03, \) and +0.10, respectively.

3. The Fainter Components of the 9 Aur System

Table II summarizes the observed properties of the other stars in the 9 Aur system. Additional measurements and comments on these stars are given below. Proper motions and parallaxes have not been reported for the fainter components. We assume the same distance modulus for them as for 9 Aur A.

3.1 The B Component

A low resolution K-band spectrum of this star was obtained on 1992 January 7 UT at UKIRT, using the facility spectrometer, CGS4 (Mountain et al. 1990). No spectral features were clearly seen, but a weak CO band was marginally detected. A similar spectrum of the primary revealed only a Br g absorption line, as expected for an F star.

Koornneef (1983) gives V-K = 3.75, J-K = 0.89, and H-K = 0.21 for an M2 dwarf star. Both the colors of the B component and its K-band spectrum are consistent with this classification. The optical photometry of the primary included the light of the B component. As the magnitude of
the variations in the photometry corresponds to variations of 4 magnitudes in the B component, it is unlikely that the B component is responsible for them.

3.2 The C Component

Griffin (1992, private communication) has measured the radial velocities of the C star and the primary. From the preliminary data the two radial velocities differed by only 3.8 km/sec, suggesting that the C component is in fact a companion. The visual magnitude and colors (Table II) imply that the C component is an early-to-middle K dwarf (see Allen 1973, p. 106)

3.3 The D Component

Spectroscopy of 9 Aur D by P. Hendry and J. Thomson on 1992 May 5, covering the interval 6330-6785 Å, shows numerous metallic lines in addition to Hα absorption (Bolton 1992, private communication). A radial velocity of $+13.1 \pm 1.0$ km/sec was derived by comparison to HD 107328, whose radial velocity was assumed to be $+35.7$ km/sec. The radial velocity suggests that the D component is not a member of the 9 Aur system. Other indicators of this are its visual magnitude and B-V color, which place it below the main sequence yet above the white dwarf cooling track, and are not consistent with any known type of star if it is at the distance of 9 Aur A. Therefore, it appears most likely that 9 Aur D is a distant K giant.

3.4 The E Component

The implied absolute magnitude and color of this object are similar to those of some white dwarfs (McCook & Sion 1987). The E star may be a white dwarf companion of 9 Aur, but it could also be a more distant main sequence star. Spectroscopic observations are needed to test this.
4. Discussion

The motivation of this work was to find an explanation for the unexpected and unexplained photometric variability of 9 Aur A, which, apart from its variability, appears to be a normal F0 V star. This variability could be interpreted as a rotational modulation of activity in the atmosphere of the star. If the star is viewed close to pole-on, as is suggested in §2.5, the time scale for variability might be the time scale for the growth and decay of disturbances, rather than the rotational period. It is also possible that (non-radial) pulsations are the cause of the variation; further radial velocity data are required to test this.

9 Aur A has few spectroscopic anomalies. However, Coupry & Burkhart (1992) found that the Fe I 6678 Å and Ca I 6717 Å absorption lines were asymmetric, with blue wings. They and Provost & van’t Veer-Menneret (1969) note the star’s high microturbulence velocity. It may be relevant to determine if these anomalies are variable.

As 9 Aur A appears to be intrinsically variable, it is of interest to know if there are other similar stars. Two early F stars with normal UBV colors and unexplained variability similar to 9 Aur are γ Dor (Cousins 1992) and HD 96008 (Lampens 1987; Matthews 1990). γ Dor has two periods, each near 3/4 day, which suggests non-radial stellar pulsations. HD 96008 has a period of 0.31 days. Matthews notes that the variability of HD 96008 is not satisfactorily explained by rotation, given the implied rotational speed of 330 km/sec, but that δ Scuti-type pulsation is not satisfactory either due to the combination of period and luminosity (i.e. the observed period is too long for a normal δ Scuti star). In short, 9 Aur, γ Dor, and HD 96008 are three
similar stars whose variability still remains unexplained.

Other F stars with unusual colors similar to those of 9 Aur A are BS 4825/6 and BS 4914. One of the former pair is variable with a range of 0.03 mag (Hoffleit & Jaschek 1982). BS 4914 is the companion of $\alpha^2$ CVn, a prototypical magnetic rotator. Photometry of other early F dwarf stars with B-V redder than “average”, U-B bluer than “average”, and moderate rotational velocities may reveal other small amplitude variables. Examples are BS 5074, 5075, and 6600. Two stars of similar color with high rotational velocities, which should be investigated, are BS 463 and BS 7887.

Because the “true” period(s) of variation for 9 Aur have not been determined, further coordinated photometry by observers situated around the globe would be useful. Unfortunately, 9 Aur is too bright to be a target of the Whole Earth Telescope (Nather & Winget 1992). More extensive and highly accurate radial velocity measurements also are needed. In addition to further observations, we suggest that greater scrutiny of stellar atmosphere models of early F dwarf stars is warranted.

**Summary**

The cause(s) of the photometric variations of 9 Aur A remain uncertain, although a close companion, variable obscuration, and contamination of the photometry from other members of the 9 Aur system are ruled out. Investigation of the other components of 9 Aur have led to the following conclusions: The B component appears to be an early-M dwarf and the C component is an early- to mid-K dwarf, both within the system; the E component may be
a white dwarf within the system; the D component appears to be a distant K giant.

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Note Added in Press

A fourth member of this class of early F-type “variables without a cause” is HD 164615 (Abt et al. 1983, MNRAS 272, 196; Rucinski 1985, PASP 97, 657), which is classed as F2 IV-V. Its photometric period was found to be ≈0.815 days. Abt et al. obtained 13 radial velocities which ranged 7.4 km/sec, but on the basis of the relatively large internal errors of the individual measurements concluded that the radial velocity was constant.

Griffin (1993, private communication) obtained 20 radial velocities of 9 Aur in February and March of 1993. Further analysis must be carried out on these data, but from the preliminary data a range of ≈6 km/sec is indicated, with a period of less than 3 days. Thus it seems that 9 Aur exhibits radial velocity variations on a time scale comparable to that of the photometric variations.
Figure Captions

Fig. 1 - Nightly means of differential photometry of 9 Aur vs. BS 1561. Circles: data by Guinan with a 25-cm automatic photoelectric telescope (APT) at Mt. Hopkins. Squares: data by Skillman, using a 32-cm APT. Guinan’s means are the average of 18 to 54 points per night. Skillman’s means are the average of 5 to 35 points per night. On 5 of these 14 nights 9 Aur showed evidence of linear variations on the order of 0.01 mag/hr.

Fig. 2 - The multi-wavelength flux of 9 Aur can be fitted by a Planck curve with $T = 7179$ K. From left to right, the filters are U, B, V, J, H, K, L, L’, and narrow-band M. Squares: optical data given by Hoffleit & Jaschek (1982). Dots: photometry of Geballe, using UKIRT and the single channel photometer UKT9. Triangles: data by Aspin, using UKIRT and the facility infrared array camera IRCAM. All the infrared photometry excludes the B component. Except for U and B, the conversion of magnitudes to flux in Jy was done according to the $\alpha$ Lyr flux given by Tokunaga (1986). U = 0 and B = 0 were taken to correspond to 2000 and 3700 Jy, respectively. The U-band point was excluded from the least-squares fit.

Fig. 3 - Differential V-band photometry of 9 Aur vs. BS 1561 by Skillman over the course of 5 hr 35 min on 1991 Feb 1 UT. Once the linear trend amounting to 0.01 mag/hr is removed, there are no significant periodic variations on time scales of tens of minutes (like a $\delta$ Scuti star).

Fig. 4 - Nightly V-band means of 9 Aur vs. BS 1561 obtained from 1992 Jan 31 to Feb 10 UT. X’s: data by Krisciunas at 2800-m elevation of Mauna Kea. Dots: data by Krisciunas at 4200-m Mauna Kea summit, using UH
24-inch telescope. Filled triangle: data by Luedeke (average of 27 points). 
+: data by Landis (average of 12 points). Open circle: data by Ohshima 
(average of 63 points). Open squares: data by Akazawa. Open triangles: 
data by Ohkura.

Fig. 5 - Power spectrum of 237 individual V-band differential magnitudes 
of 9 Aur vs. BS 1561, using the Lomb-Scargle algorithm (Press & Teukolsky 
1988).

Fig. 6 - Differential photometry of 9 Aur vs. BS 1561. The symbols are 
the same as in Fig. 4. The data are folded by a period corresponding to 
the most significant peak in the power spectrum. Systematic errors between 
different observers would amount to 0.01 mag or less.