MULTICOLOR PHOTOMETRY OF THE GALACTIC CLUSTER NGC 2362

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Abstract. *U, B, V* colors of CPD stars brighter than $12\overset{m}{.}0$ in the central region of NGC 2362. Color excess. Discussion of the distance modulus of the cluster.

1. Introduction

The galactic cluster NGC 2362 is a sparsely populated but tightly knit aggregate of early-type stars dominated by the fourth magnitude O-type star τ CMa. The cluster has been of considerable astronomical interest. Because it is only a few million years old, NGC 2362 has played a vital rôle in the extension of the *UBV* zero-age main sequence toward the blue and bright end of the color-magnitude diagram; see, for example, an excellent discussion by Blaauw (1963), where references are given to earlier papers also involved with the development of the main-sequence fitting procedure. Likewise, the cluster will be an important addition in the development of the *uvby* and Hβ photometric systems. Recent observational investigations of the cluster include a photometric study by Johnson (1950) and a combined *UBV* and MK classification study by Johnson and Morgan (1953). The present photometric investigation was undertaken because of both the intrinsic importance of the cluster and the variance in previous determinations of its distance.

2. Observations

All CPD stars brighter than $12\overset{m}{.}0$ within an area of the sky between $7^h13^m00^s$ and $7^h14^m20^s$ (1875) of right ascension and between $-24°35'$ and $-24°50'$ of declination were chosen as the major part of the observing program. The four non-CPD stars brighter than $12\overset{m}{.}0$, as observed by Johnson and Morgan, completed the program. Additional *UBV* observations were made to supplement the existing data. *uvby* and Hβ photometry was obtained for the majority of the stars in the immediate cluster region.

Details of the instrumentation, observing techniques, and reduction procedures have been described by Perry and Hill (1969). Table I lists the internal mean errors of a single observation. Henceforth, mean errors are quoted throughout the paper. Table II gives, in succession, the CPD numbers, the *UBV*, *uvby*, and Hβ values obtained in this investigation, along with the number of nights on which observations of a given star were made; each star was usually observed twice during a given night. The *V* magnitudes on the *UBV* system, listed in the sixth column, were derived from the *y* deflec-

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tions of the *uvby* photometry. *UBV* observations of the star $-24°2251$ were made but its photometric values are not included in Table II because its colors were outside the color range of the standard stars. It is a late-type object.

TABLE I
Internal mean errors of a single observation

V	$B-V$	$U-B$	V	$b-y$	m_1	c_1	β
$0^m_.019$	$0^m_.013$	$0^m_.017$	$0^m_.019$	$0^m_.013$	$0^m_.017$	$0^m_.019$	$0^m_.012$

The *UBV* photometries of Johnson and Morgan and Table II were combined into a homogeneous system. The V magnitudes derived from the *uvby* photometry were also included. Table III lists the CPD numbers, the Johnson numbers, the binary star numbers from the *Index Catalogue of Visual Double Stars* by Jeffers and van den Bos (1963), the final *UBV* values, along with the number of observations. The MK spectral types, listed in the last column, are due to Johnson and Morgan or Schild (1970). The photometry for the four stars indicated in the fourth column of the table refers to the combined light of the binary components.

3. Results

A. COLOR EXCESS OF NGC 2362

The intrinsic colors of the program stars were determined by four methods, namely, (1) the *UBV* Q-method, (2) Strömgren's (1966) $[u-b]$ calibration, (3) Crawford's (1970) c_0 calibration, and (4) MK spectral types. These methods will be discussed in some detail in turn.

The *UBV* color indices listed in Table III were employed to compute the individual intrinsic color indices via the equations $(B-V)_0=0.335(U-B)-0.241(B-V)$ and $(U-B)_0=1.241(U-B)-0.893(B-V)$. The coefficients in the above relations are appropriate for a reddening slope in the *UBV* color-color diagram of $E(U-B)/E(B-V)=0^m_.72$. A discussion of the *UBV* Q-method is given, for example, by Morgan and Harris (1956). Individual color excesses in both colors were next calculated via the equations $E(B-V)=(B-V)-(B-V)_0$ and $E(U-B)=(U-B)-(U-B)_0$. The twenty-nine program stars, selected as clusters members, yielded mean cluster color excesses of $E(B-V)=0^m_.100\pm0^m_.020$ and $E(U-B)=0^m_.070\pm0^m_.014$. The questions of cluster membership is discussed in the next section.

Figure 1 illustrates the *UBV* color-color diagram for NGC 2362 plotted with the data in Table III. The solid line traces the standard relation derived by Johnson and Morgan, shifted by $0^m_.10$ in $(B-V)$ and $0^m_.07$ in $(U-B)$. The small scatter about the standard relation indicates that the reddening is nearly uniform over the cluster region.

An ultraviolet color index for the *uvby* photometric system may be derived via the

TABLE II

Multicolor photometry of NGC 2362

CPD	V	B−V	U−B	n	V	b−y	m_1	c_1	n	β		Notes
−24°2182	$9^{\mathrm{m}}.31$	$-0^{\mathrm{m}}.11$	$-0^{\mathrm{m}}.76$	5								(1)
	11. 80	0. 48	0. 02	4								
−24°2185	8. 91	−0. 13	−0. 84	5								
−24°2188	10. 05	−0. 08	−0. 66	6								
−24°2195					$11^{\mathrm{m}}.40$	$0^{\mathrm{m}}.027$	$0^{\mathrm{m}}.092$	$0^{\mathrm{m}}.721$	2	$2^{\mathrm{m}}.724$	2	
−24°2196					10.76	0.006	0.086	0.086	2	2.699	2	
−24°2197										2.796	2	
−24°2198					11.17	−0.001	0.123	0.534	2	2.738	2	
−24°2199	11.46	−0.02	−0.32	4	11.46	0.036	0.091	0.584	2	2.768	2	
−24°2200	11.93	−0.01	−0.22	4	11.93	0.036	0.107	0.745	2			
−24°2201	10.50	0.10	0.08	4						2.851	2	
−24°2203					9.80	−0.030	0.101	0.262	4	2.676	2	
−24°2204					9.98	−0.016	0.084	0.306	3	2.705	2	
−24°2205					9.48	−0.038	0.084	0.152	5	2.656	2	
−24°2206					11.75	0.031	0.128	0.817	2			
−24°2207					9.51	−0.044	0.086	0.105	5	2.650	2	
−24°2208										2.798	2	
	11.63	0.24	0.10	4								(2)
−24°2211	11.90	0.00	−0.20	3	11.90	0.032	0.128	0.733	2			
−24°2212					10.43	−0.008	0.088	0.373	2	2.674	2	
−24°2213					8.76	−0.053	0.080	−0.021	5	2.620	2	
					9.48	−0.047	0.055	0.105	5	2.658	2	(3)
	11.91	0.01	−0.19	4	11.91	0.043	0.097	0.796	2			(4)
−24°2216	4.39	−0.15	−1.00	std	4.39	−0.045	0.065	−0.141	std	2.564	std	
−24°2217	10.98	−0.04	−0.43	4	10.98	0.018	0.091	0.477	2	2.714	2	
−24°2218	10.77	0.00	−0.42	7	10.77	0.028	0.108	0.500	2	2.741	2	
−24°2220										2.736	2	
−24°2221	10.60	0.15	0.09	4								
−24°2222	11.91	0.06	−0.19	4	11.91	0.080	0.104	0.717	2			

Table II (continued)

CPD	V	$B-V$	$U-B$	n	V	$b-y$	m_1	c_1	n	β		Notes
−24°2223					10.38	−0.026	0.117	0.363	2	2.685	2	
−24°2225					10.15	−0.045	0.107	0.228	3	2.692	2	
−24°2226	10.76	0.28	0.22	5						2.800	2	
−24°2228					$8^m.18$	$-0^m.063$	$0^m.070$	$-0^m.044$	5	$2^m.614$	2	
−24°2230	$11^m.33$	$-0^m.04$	$-0^m.33$	6	11.33	0.023	0.089	0.644	2	2.746	2	
−24°2231					9.30	−0.044	0.083	0.090	5	2.636	2	
−24°2232	11.06	−0.05	−0.52	4								
−24°2235	10.91	0.16	0.12	3	10.91	0.130	0.143	1.088	2			
−24°2236	10.50	−0.03	−0.49	3	10.50	0.025	0.094	0.364	2	2.704	2	
−24°2240										2.689	2	
−24°2244	11.34	−0.01	−0.38	7	11.34	0.035	0.085	0.577	2	2.739	2	
−24°2246	10.39	0.44	−0.02	5								
−24°2248	6.80	−0.16	−0.72	std	6.80	−0.073	0.089	0.219	std	2.634	std	
−24°2250	9.79	−0.05	−0.55	5								
−24°2253	10.75	0.27	0.13	5								
−24°2254	10.70	0.01	−0.10	4								

Notes to Table II
(1) Johnson No. 64.
(2) Johnson No. 65
(3) Johnson No. 39
(4) Johnson No. 22.

TABLE III

Combined *UBV* photometry of NGC 2362

CPD	Johnson		*V*	*n*	*B – V*	*n*	*U – B*	*n*	Spt
–24°2182			$9^{\mathrm{m}}31$	5	$-0^{\mathrm{m}}11$	5	$-0^{\mathrm{m}}76$	5	
	64		11.80	6	0.48	6	0.02	4	
–24°2185			8.91	5	–0.13	5	–0.84	5	B8
–24°2188			10.05	6	–0.08	6	–0.66	6	
–24°2195	1		11.39	5	0.00	3	–0.28	3	
–24°2196	5		10.77	5	–0.06	3	–0.52	3	B5V:
–24°2197	3		11.05	3	0.09	3	–0.15	3	
–24°2198	2		11.18	5	–0.02	3	–0.38.	3	
–24°2199	66		11.46	8	–0.02	6	–0.32	6	
–24°2200	11		11.93	8	0.00	6	–0.22	4	
–24°2201	13		10.49	6	0.10	6	0.08	6	
–24°2203	9		9.82	7	–0.08	3	–0.61	3	B3V
–24°2204	12		10.00	6	–0.07	3	–0.57	3	B3:nn
–24°2205	48		9.50	8	–0.11	3	–0.69	3	B3V
–24°2206	15		11.76	5	0.03	3	–0.14	3	B9V:
–24°2207	14		9.54	8	–0.12	3	–0.73	3	B2V
–24°2208	16		10.57	3	0.07	3	–0.20	3	B9V:
	65		11.64	6	0.24	6	0.10	4	
–24°2211			11.90	5	0.00	3	–0.20	3	
–24°2212	21		10.44	5	–0.07	3	–0.51	3	B3Vn
–24°2213	20		8.77	9	–0.15	4	–0.87	4	B1.5V
	39		9.48	5	–0.09	3	–0.67	3	B2V
	22		11.92	8	0.01	6	–0.19	4	
–24°2216	23	250 – 07(AB)/10(Ap)	4.39	std	–0.14	std	–1.00	std	09III
–24°2217	24		10.99	8	–0.04	6	–0.43	6	B7nn
–24°2218	25		10.77	10	0.00	8	–0.42	8	
–24°2220	50		10.20	3	0.00	3	–0.36	3	B6V
–24°2221		250 – 06(AB)	10.60	4	0.15	4	0.09	4	
–24°2222	52		11.92	8	0.05	6	–0.19	4	
–24°2223	26		10.41	5	–0.07	3	–0.52	3	B5V
–24°2225	30		10.16	6	–0.07	3	–0.58	3	B3V
–24°2226	32		10.76	6	0.28	6	0.22	5	
–24°2228	30	250 – 09(D)	8.20	10	–0.17	5	–0.91	5	B1V
–24°2230	29		11.33	9	–0.04	7	–0.33	7	
–24°2231	31		9.31	8	–0.12	3	–0.76	3	B2V
–24°2232			11.06	4	–0.05	4	–0.52	4	
–24°2235			10.91	5	0.16	3	0.12	3	
–24°2236	34		10.50	7	–0.03	5	–0.49	5	B5V
–24°2240	36		10.76	3	0.02	3	–0.48	3	B7:nn
–24°2244	42		11.34	11	–0.01	9	–0.38	7	
–24°2246			10.39	5	0.44	5	–0.02	5	
–24°2248	46	250 – 50(AB)	6.80	std	–0.16	std	–0.72	std	B2IV
–24°2250		50 – 49(AB)	9.79	5	–0.05	5	–0.55	5	
–24°2253			10.75	5	0.27	5	0.13	5	
–24°2254			10.70	4	0.01	4	–0.10	4	

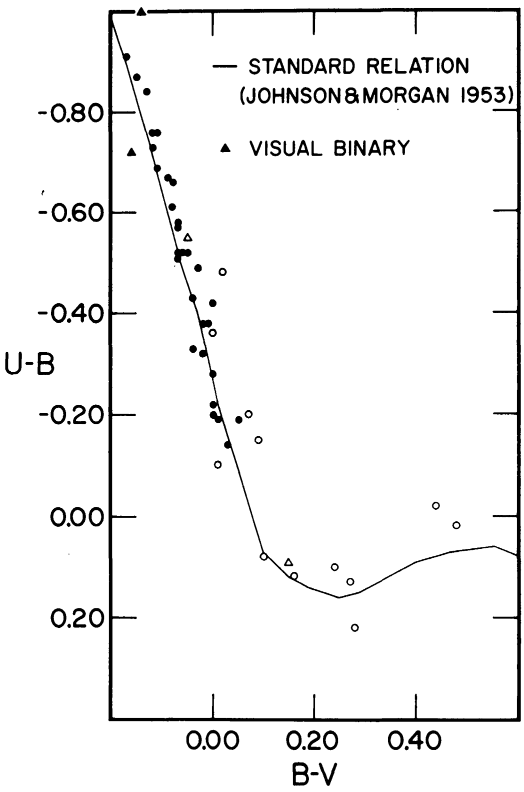

Fig. 1. The *UBV* color-color diagram for NGC 2362. The solid line traces the standard relation of Johnson and Morgan (1953). Visual binaries are indicated.

equation $(u-b)=c_1+2m_1+2(b-y)$. Strömgren (1966) has formed an index $[u-b]$ which is independent of interstellar reddening; the index is given by the equation $[u-b]=(u-b)-1.84(b-y)$. On the basis of *uvby* photometry of nearby and hence unreddened B stars, Strömgren found that $(b-y)_0$ is a function of $[u-b]$ only. After values of $(u-b)$ and $[u-b]$ were computed for those stars in Table II with *uvby* photometry, the intrinsic $(b-y)_0$ colors were interpolated from Strömgren's calibration. Individual color excesses were next calculated via the equation $E(b-y)=(b-y)-(b-y)_0$. The nineteen program stars, selected as cluster members, yielded a mean cluster color excess of $E(b-y)=0^m.090\pm0^m.022$. Crawford (1964) has shown that the color excesses in the *UBV* and *uvby* photometric systems are related by the equation $E(B-V)=1.43E(b-y)$; the above value of $E(b-y)$ is therefore equivalent to $E(B-V)=0^m.129\pm0^m.031$.

On the basis of *uvby* photometry of bright and hence unreddened B stars, Crawford (1970) has devised an iterative procedure to determine the intrinsic $(b-y)_0$ colors of early-type stars. One employs the observed c_1 values to obtain the first approximation to the $(b-y)_0$ colors via the equation $(b-y)_0=-0.116+0.097c_1$. The color excesses are computed in the usual manner. Crawford (1966) has shown that the color excesses in $(b-y)$ and c_1 are related by the equation $E(c_1)=0.2E(b-y)$. The observed c_1 values are corrected for reddening via the equation $c_0=c_1-E(c_1)$. The second approximation to the $(b-y)_0$ colors is obtained by substituting c_0 in place of c_1 in the first equation. One iteration was sufficient to calculate the individual $(b-y)_0$ colors and color excesses for those stars in Table II with *uvby* photometry. The twenty-three program stars, selected as cluster members, yielded a mean cluster color excess of $E(b-y)=0\overset{m}{.}075\pm0\overset{m}{.}015$. This value corresponds to $E(B-V)=0\overset{m}{.}107\pm0\overset{m}{.}021$.

The tabulation by Johnson (1963) of intrinsic $(B-V)_0$ and $(U-B)_0$ colors as a function of MK spectral type allows one to determine the $(B-V)_0$ colors for those program stars listed in Table III with MK spectral types. Individual color excesses were next computed. The fifteen program stars, selected as cluster members, yielded a mean cluster color excess of $E(B-V)=0\overset{m}{.}112\pm0\overset{m}{.}022$.

B. DISTANCE MODULUS OF NGC 2362

The absolute magnitudes of the program stars were also determined by four methods, namely, (1) the intrinsic $(B-V)_0$ colors, (2) Fernie's (1965) (β, M_v) calibration adopted by Strömgren (1966), (3) Crawford's (1970) (β, M_v) calibration, and (4) MK spectral types. These methods will be discussed in some detail in turn.

In all four methods, the visual apparent magnitudes were corrected for interstellar absorption via either the equation $V_0=V-3.0E(B-V)$, derived by Morgan, Harris, and Johnson (1953), or $V_0=V-4.3E(b-y)$, derived by Crawford (1966).

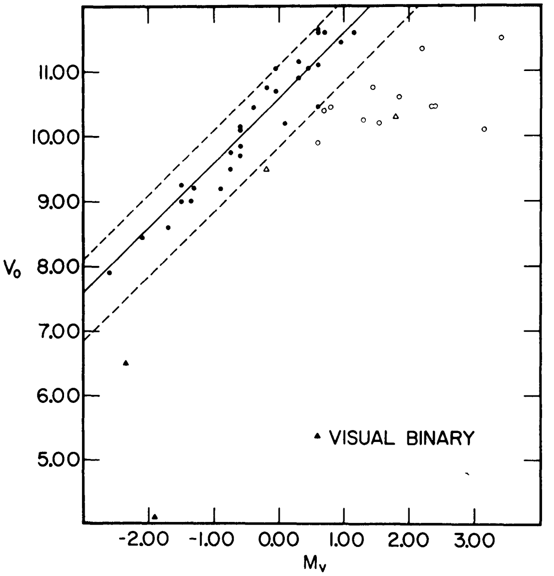

Fig. 2. The $UBV(V_0,M_v)$ diagram for NGC 2362. Probable cluster members are denoted by filled circles, non-members by open circles. Visual binaries are indicated. The dashed lines are discussed in the text.

Following the example of Walker (1965), cluster membership was investigated by means of (V_0, M_v) diagrams in all four methods. Figure 2 illustrates the UBV (V_0, M_v) diagram for NGC 2362. Stars within the domain defined by the dashed lines are considered to be cluster members. These limits were set by assuming that no cluster member will lie more than $0^m.5$ above the line $V_0 = M_v +$ constant and that duplicity will not brighten a star more than $0^m.75$. The brightest members of a cluster may lie outside the membership domain because they are in the process of evolving away from the main sequence.

Blaauw (1963) has tabulated visual absolute magnitude as a function of $(B-V)_0$ for the zero-age main sequence. The twenty-seven program stars, selected as cluster members, in Table III with UBV photometry yielded a mean cluster distance modulus of $10^m.60 \pm 0^m.26$.

Figure 3 illustrates the UBV color-magnitude diagram for NGC 2362. The solid line traces Blaauw's ZAMS. The absolute magnitude scale on the right-hand side of the diagram is computed for a distance modulus of $10^m.60$.

Strömgren (1966) adopted Fernie's (1965) (β, M_v) calibration. The calibration was derived using various galactic clusters and associations with well-determined distance

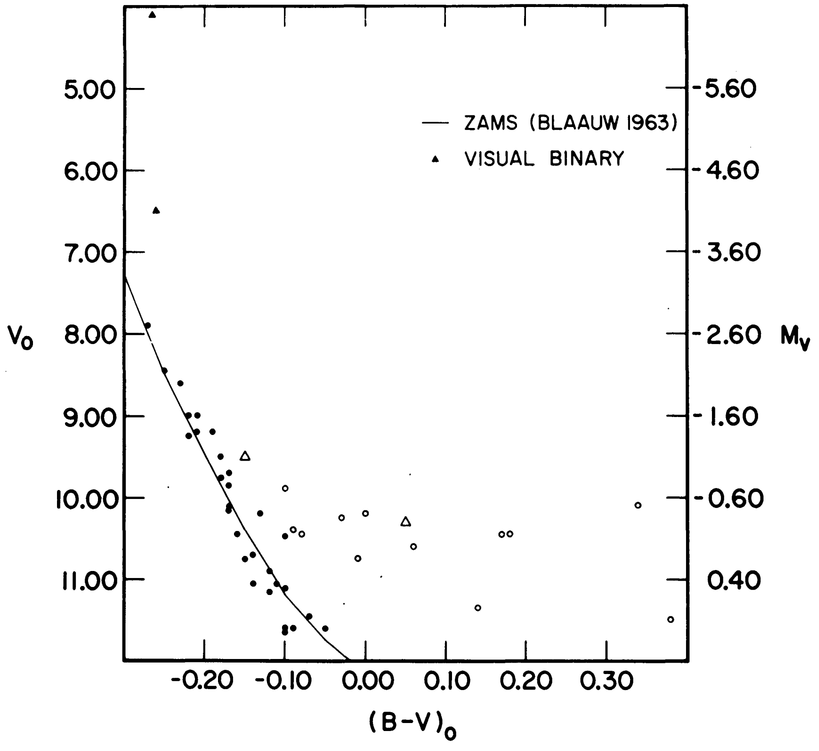

Fig. 3. The UBV color-magnitude diagram for NGC 2362. Visual binaries are indicated. The solid line traces Blaauw's (1963) zero-age main sequence. The absolute magnitude scale on the right-hand side of the diagram is computed for a distance modulus of $10^m.60$.

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moduli; the cluster members had measured hydrogen line intensities which Fernie reduced to the photoelectric β system. The nineteen program stars, selected as cluster members, in Table II with Hβ photometry yielded a mean cluster distance modulus of $11^m.22 \pm 0^m.24$.

Crawford (1970) derived his (β, M_v) calibration by fitting the shape of the (V_0, β) relations of various galactic clusters and associations; the zero point of the calibration was defined by the known distance moduli of the α Persei and Pleiades clusters. The eighteen program stars, selected as cluster members, in Table II with Hβ photometry yielded a mean cluster distance modulus of $11^m.22 \pm 0^m.26$.

The tabulation by Blaauw (1963) of absolute magnitude as a function of MK spectral type also allows one to determine the absolute magnitudes of those stars in Table III with MK spectral types. The fifteen program stars, selected as cluster members, yielded a mean cluster distance modulus of $11^m.27 \pm 0^m.30$.

4. Discussion

Table IV includes a summary of the results from the four determinations of the mean cluster color excess and corrected distance modulus of NGC 2362 made in this paper. The adopted values are averages of the four determinations weighted according to their mean errors, with the following exception. Because the (β, M_v) calibrations of Fernie and Crawford are quite similar, only one value of $V_0 - M_v = 11^m.22$ was included in the weighted average. It should be pointed out that the color excess and distance modulus determined from the MK spectral types is not strictly compatible with the values determined by the three other methods. The former determination refers to stars found within the main-sequence band while the three latter determinations refer to the ZAMS. In addition, Table IV lists the previous determinations by Johnson, and Johnson and Morgan. In both of these papers, the authors assumed that interstellar reddening in the cluster was negligible.

Other investigators, including Johnson and Hiltner (1956), Sandage (1957), Johnson (1957), Johnson and Iriarte (1958), and Blaauw (1963) have derived estimates of the color excess and corrected distance modulus of the cluster by the main-sequence fitting

TABLE IV

Summary of reddening and distance determinations

Source	Type	$\bar{E}(B-V)$	No.	$\overline{V_0 - M_v}$	No.
Johnson (1950)		$0^m.00$		$10^m.75$	
Johnson and Morgan (1953)	*UBV*	0.00		11.9	
Perry's Method No. 1	MK	0.112 ± 0.022	15	11.27 ± 0.30	15
Perry's Method No. 2	*UBV*	0.100 ± 0.020	29	10.60 ± 0.26	27
Perry's Method No. 3	*uvby* – Hβ	0.129 ± 0.031	19	11.22 ± 0.24	19
Perry's Method No. 4	*uvby* – Hβ	0.107 ± 0.021	23	11.22 ± 0.26	18
Perry's Adopted Mean		0.109		11.02	

procedure. Their estimates cluster about the values of $E(B-V)=0\overset{m}{.}11$ and $V_0-M_v=10\overset{m}{.}8$.

As stated above, the question of cluster membership was investigated by means of (V_0, M_v) diagrams. The *UBV* analysis indicates that 14 of the 45 program stars (Johnson No. 64, −24°2197, −24°2201, −24°2208, Johnson No. 65, −24°2220, −24°2221, −24°2226, −24°2235, −24°2240, −24°2246, −24°2250, −24°2253, and −24°2254) are not cluster members. The other three analyses almost always confirm this conclusion.

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