V818 Scorpii: Insights From the AAVSO and RASNZ Databases

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Abstract Insight into the Low Mass X-ray Binary system V818 Scorpii (Scorpius X-1) is gained from an examination of the visual databases of the American Association of Variable Star Observers (AAVSO) and the Variable Star Section of the Royal Astronomical Society of New Zealand (RASNZ). A correlation is found between these visual estimates and EXOSAT X-ray observations. While such a correlation has long been known to exist from *B*-magnitude photometric studies, no such work is known with the AAVSO and the RASNZ data.

1. Introduction

V818 Scorpii (Scorpius X-1) was the first X-ray source discovered outside the solar system, in 1962. The system, also called a Low Mass X-ray Binary, is thought to be a stellar-mass compact object with an accretion disk, and a secondary donor star of around one solar mass (van den Heuvel and van Paradijs 2004). The stars in this system are only 1 or 2 million kilometers apart, and orbit a common center in 18 hours 53 minutes. The compact primary is almost certainly a neutron star, an object with a mass of more than 1.4 times that of the Sun and having a radius of ~10km (Mirabel and Rodrigues 2003; Revnivtsev and Gilfanov 2003).

Because of the extreme gravity of the primary, accreting matter crashing onto the neutron star releases much more energy per gram than does thermonuclear fusion (van den Heuvel and van Paradijs 2004). Infalling matter is heated to 100 million K, and X-rays are generated along with other radiation across the electromagnetic spectrum. The accretion process in X-ray binaries such as V818 Sco is complex, and results in erratic behavior in all parts of the electromagnetic spectrum. For example, X-ray variability has been observed on timescales of milliseconds to many hours (Revnivtsev and Gilfanov 2003; van der Klis 2005).

Much of the short term optical variability is believed to be caused by reprocessed X-ray emission. The accretion of blobs or filaments of material by the neutron star causes variable X-ray emission, and this emission is then "reprocessed" (lowered in energy) in the accretion disk of the system, resulting in the optical variability. The more slowly changing global accretion rate then results in longer-term changes at both X-ray and optical wavelengths (van der Klis 2005).

2. The X-ray observations

A "Z source" is a Low Mass X-ray Binary whose plot of observations made in two X-ray colors forms the shape of the letter Z. This color-color diagram is called a *Z diagram*. V818 Sco is a “Z source,” even though its Z diagram is not perfectly Z-shaped (see Figure 1). The solid line and shaded area in this figure represent the Z track, a result of thousands of X-ray observations. This figure is adapted from Figure 1 of Dieters and van der Klis (2000), who analyzed 1985–1986 EXOSAT data. The numerical values on the diagram are temporally coincident visual magnitude estimates discussed below.

The three branches on the Z diagram are the Horizontal, the Normal, and the Flaring Branches—HB, NB, and FB, respectively. This corresponds to different X-ray states, with the accretion rate generally increasing with movement from the top of the Z track to the bottom. Movement along the Z track is gradual, and does not jump (van der Klis 2005; McNamara *et al.* 2003, 2005).

Although the pattern shown in Figure 1 does not look much like a “Z,” the other members of this small family of objects (such as Cyg X-2) do show a full Z in their X-ray color-color plots. V818 Sco has a more bi-modal pattern, because of the object apparently spending very little time on its HB. A corresponding bi-modal pattern is expected from the visual estimates, if there is indeed a correlation between the visual and X-ray activity.

3. The visual observations

Visual data available in this report include the entire validated data set from the AAVSO (JD 2439591–2452815, 1967–2003) and the available data set from the RASNZ (JD 2446883–2453491, 1987–2005, including observations made by the author). These are presented in total as Figures 2 and 3, with “fainter-than” and “uncertain” observations omitted. Histograms are used to present the data because the information of interest here is the amount of time spent in each state—in other words, how many observations are at which level—so a conventional light curve would be less useful here.

Figures 4a–4j are a breakdown of the AAVSO data by observer. Observers with less than thirty or so estimates are omitted. This breakdown was only available with the AAVSO data. Figures 5a–5n are the combined AAVSO and RASNZ data, where they overlap for 1987–2003, in 400-day lots. These figures are presented in temporal order.

The visual estimates overlaid onto Figure 1 are a special case: They are the very few coincident with X-ray observations. Fortunately they are all by the same observer, M. Daniel Overbeek (OB, Table 1). It is appropriate to thank Mr. Overbeek here: 2,263 of the visual data points in this report are his. This consistency over many years is significant and valuable.

4. The correlation: X-ray state and visual variability

The accretion rate is highest when V818 Sco is on its FB, with escaping X-rays irradiating a portion of the accretion disk. These are reprocessed into visual light, resulting in the brighter visual magnitudes (Hynes 2005). McNamara *et al.* (2005) have found that the Johnson *B* magnitude of V818 Sco directly correlates to its X-ray emission, up to the mid-point of the FB. Past this point the emission is then characterized by intense short term flares that make the *B* band highly variable.

Figure 1 shows two time-specific visual estimates by OB at magnitude 11.6 when the object was determined to be on the FB. It is interesting to note that there is a smattering of observations up to magnitude 11.0 (see Figures 2 and 3), and it is very possible that these observations are of such flares as McNamara (2005) observed, past the mid-point of the FB.

The higher frequency of X-ray observations at the joining of the FB and NB is reflected by the visual observation peaks around magnitude 11.8–12.1 of Figures 2, 3, 4a, and on through much of the presented data.

Because of increasing opacity coincident with increasing accretion flow, the X-ray flux is observed to decrease with movement down the NB. This is very complicated, and the reader is directed to Psaltis *et al.* (1995) and McNamara *et al.* (2003, 2005) for a proper description. Suffice to say here that it is predicted that as the X-ray flux increases up the Z diagram, the optical flux decreases. The estimates by OB of magnitude 12, 12.1, and 12.4 overlaid onto Figure 1 as V818 Sco moves up the NB are indicative of this.

The visual histograms of Figures 2 and 3 again match the EXOSAT data of Figure 1, showing fewer “mid” magnitude observations. (There is a peak at magnitude 12.4 in some of the data, possibly attributable to observer bias, resulting from a “124” comparison star on the chart (Templeton 2005)).

The many EXOSAT observations at the boundary of the NB and HB show that the object spends a great deal of time in that state, and Figures 2 and 3 show this second peak at the fainter magnitudes also. The bi-modal nature of the color-color diagram is found in the large data sets of Figures 2 and 3, and the next largest data set from OB. Of the twenty-three remaining figures presented here, all but one (Figure 4d) show either the bi-modal pattern, or one or other of the peaks.

On the HB, the irradiated matter is blown away, leaving a spectrum dominated by hard X-rays (Revnivtsev and Gilfanov 2003; van der Klis 2005). Figure 1 shows that V818 Sco spends little time on the HB, where it is optically at its faintest. The decreasing number of visual estimates from magnitude 13.2 down to a lone observation at 14th magnitude show this also.

5. Discussion and speculations

Five of the ten individual observers plotted through Figures 4a–4j show a clear bi-modal pattern. Of the rest, two show the faint peak, two show the brighter one, and one (Figure 4d) is hard to categorize. Thus the bi-modal pattern seems certain, and not some random artefact. This is in line with long standing *B*-magnitude photometric studies, and linked to X-ray state and accretion flow (for instance, Hiltner and Mook 1970; Augusteijn *et al.* 1992; McNamara *et al.* 2003, 2005; van der Klis 2005).

In light of the above discussion, there is every reason to believe that the time-series of 400-day histograms presented in Figures 5a–5n (1987–2003) capture at least an impression of the changing nature of V818 Sco over those years. In the absence of parallel X-ray data, one could speculate that for the first two 400-day periods the system spent more time than not at the top of its NB, with its harder X-ray state, and dimmer accretion disk. Possibly the situation reversed for the next few years, with a more illuminated accretion disk. The next few years show the bi-modal pattern, followed by an unusual period (Figure 5m) of time on the HB. This is with the hardest of X-ray states, and very little illuminated accreting mater, leaving more of the faintest visual estimates.

6. Conclusion

The X-ray state of V818 Sco has previously been linked to accretion behavior, therefore a relationship between visual estimates and accretion is implied, although not proven. It has been shown that variable star observations of V818 Sco contained in the databases of the AAVSO and the RASNZ provide some small insight into the behavior of this system. Furthermore, it is apparently possible for even one consistent observer with a 20-cm telescope to follow the changing nature of this system over years. That any insight at all can be had into such an exotic system as this, by amateur observers, is exciting news. This object is likely to be well observed in X-rays for some time to come, and presents good chances for coincident observation by amateurs in visual, *B* and *V* photometric bands. If X-ray observations were to cease for some reason, these other techniques seem definitely useful.

7. Acknowledgements

I acknowledge with thanks the variable star observations from the AAVSO International Database contributed by observers worldwide and used in this research. Also, I thank the Variable Star Section of the Royal Astronomical Society of New Zealand, and in particular Ranald McIntosh. Matthew Templeton from the AAVSO has provided invaluable assistance, and the Sydney City Sky Watchers have provided the motivation for the work.

References

Augusteijn, T., *et al.* 1992, *Astron. Astrophys.*, **265**, 177.

Dieters, S. W., and van der Klis, M. 2000, *Mon. Not. Roy. Astron. Soc.*, **311**, 201.

Hiltner, W. A., and Mook, D. E. 1970, *Astron. Astrophys.*, **8**, 1.

Hynes, R. I. 2005, "Correlated X-Ray and Optical Variability in X-Ray Binaries" in *The Astrophysics of Cataclysmic Variables and Related Objects*, ASP Conference Series Vol. 330, J. M. Hameury, and J. P. Lasota, eds., p. 237.

McNamara, B. J., *et al.* 2003, *Astron. J.*, **125**, 1437.
McNamara, B. J., Norwood, J., Harrison, T. E., Holtzman, J., Dukes, R., and Barker, T. 2005, *Astrophys. J.*, **623**, 1070.
Mirabel, I. F., and Rodrigues, I. 2003, *Astron. Astrophys.*, **398**, L25.
Psaltis, D., Lamb, F. K., and Miller, G. S. 1995, *Astrophys. J.*, **454**, L137.
van den Heuval, E. P. J., and van Paradijs, J. V. 2004, *Sci. Am.*, **14**, 58.
van der Klis, M. 2005, *Mon. Not. Roy. Astron. Soc.*, **358**, 860.
Revnivtsev, M. G., and Gilfanov, M. R. 2003, *Astron. Astrophys.*, **410**, 217.
Templeton, M. 2005, private communication.

Table 1. Observing runs of V818 Sco roughly co-incident with visual estimates by Overbeek (OB). Based on Deiters and van der Klis (2000).

Description	*Julian Date*	*X-ray state and Visual Magnitude*
X-ray observing run	2445915.7–916	NB moving to FB
Observation by OB	2445915.216	12.4
X-ray observing run	2446301.8–302.1	FB
Observation by OB	2446300.2	11.6
X-ray observing run	2446303.8–304.1	Just entered NB
Observation by OB	2446304.2	12
X-ray observing run	2446304.7–305.1	FB moving to NB
Observation by OB	2446305.25	11.6
X-ray observing run	2446503.3–503.55	Low NB
Observation by OB	2446503.6	12.1

Note: The estimation of the X-ray state is from Deiters and van der Klis 2000, however the "just entered NB" is my judgment, based on the observation run approximately an hour before the one shown.

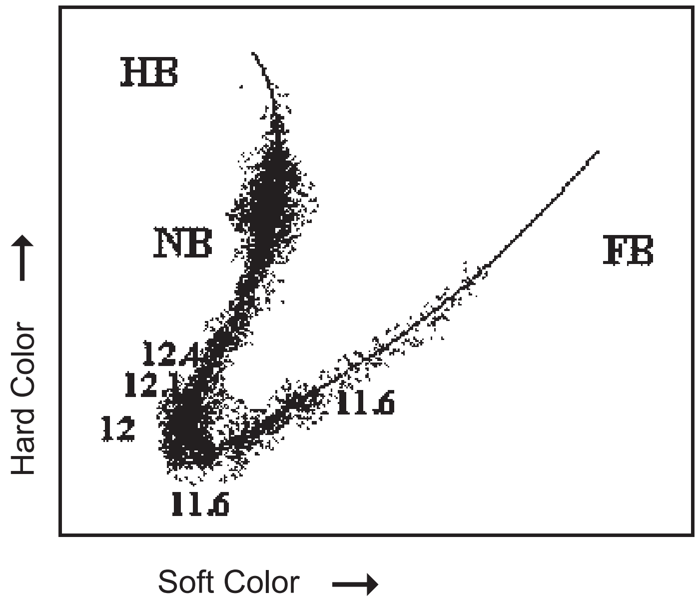

Figure 1. An estimation of the Z track (line) and X-ray observations (shaded area), adapted from Dieters and van der Klis (2000) figure 1, using 1984–1986 EXOSAT data. The numbers are single visual observations by OB contemporaneous with specific X-ray observation runs. See Table 1 for the combined log of observations. It is seen that the object is optically brighter on the FB, and dims as it moves up the NB. V818 Sco is hardly ever present on its HB, where it is optically faintest.

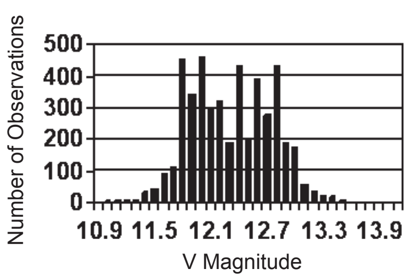

Figure 2. AAVSO: 4,528 points.

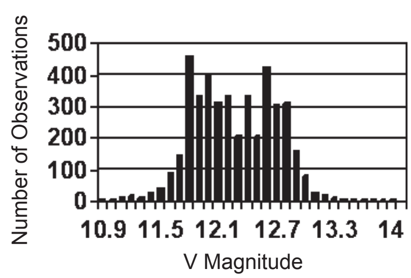

Figure 3. RASNZ: 4,262 points.

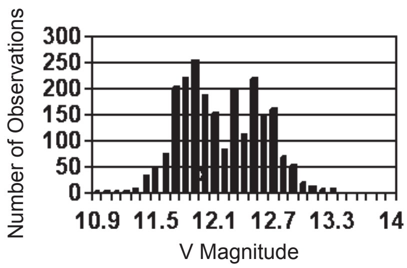

Figure 4a. OB: 2,263 points.

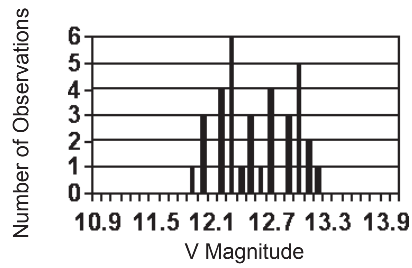

Figure 4b. BLD: 34 points.

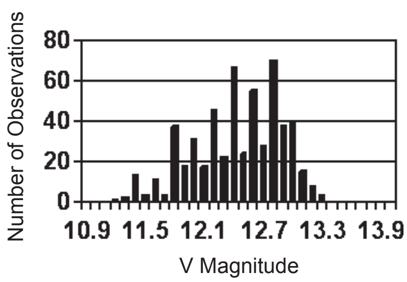

Figure 4c. BRJ: 547 points.

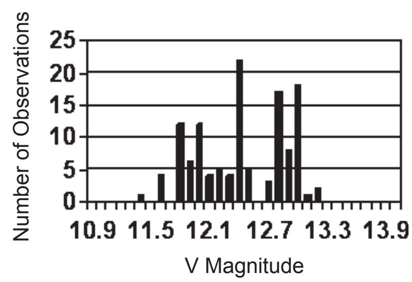

Figure 4d. CR: 128 points.

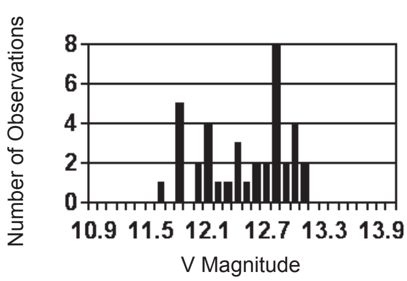

Figure 4e. HK: 38 points.

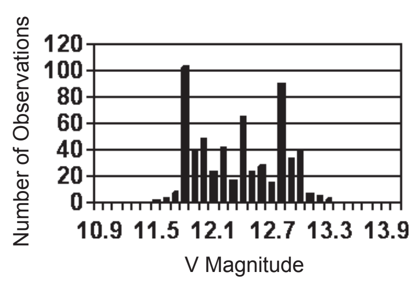

Figure 4f. JA: 585 points.

Figures 4a–4f. AAVSO data on V818 Sco broken down into individual observers. Observers having made fewer than 30 estimates of the star are not included here. A bi-modal pattern is easily seen in the individual data sets, even though some observers show only the dimmer or brighter peaks. *(Figure 4 continued on next page.)*

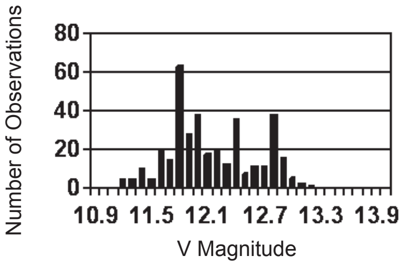

Figure 4g. MLF: 358 points.

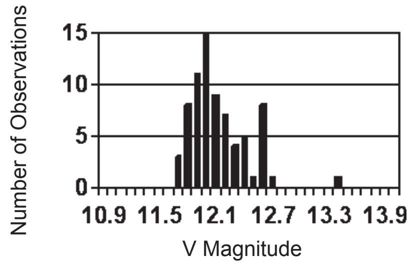

Figure 4h. SNO: 73 points.

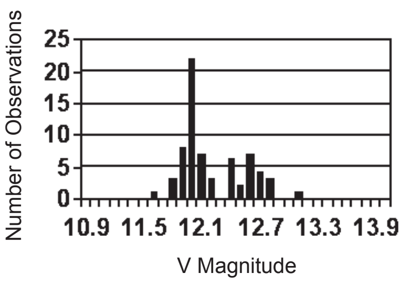

Figure 4i. SRX: 67 points.

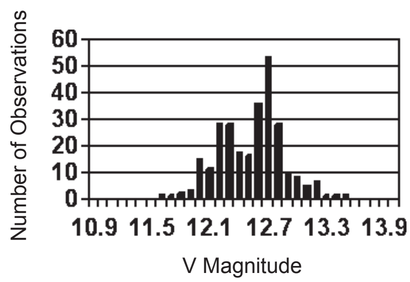

Figure 4j. YRK: 271 points.

Figures 4g–4j. AAVSO data on V818 Sco, cont. *(See preceding page for details.)*

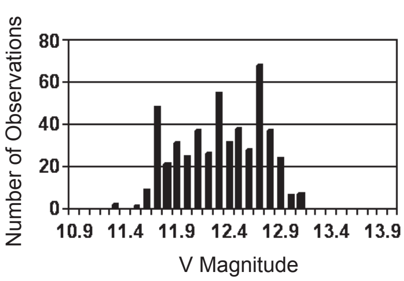

Figure 5a. 494 points.

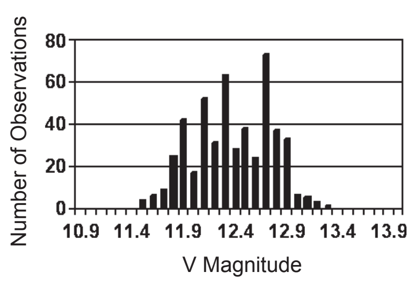

Figure 5b. 581 points.

Figures 5a–5b. Combined AAVSO and RASNZ data on V818 Sco, from 1987 to 2003. Figures are in 400-day lots and in temporal order. *(Figure 5 continued on next page.)*

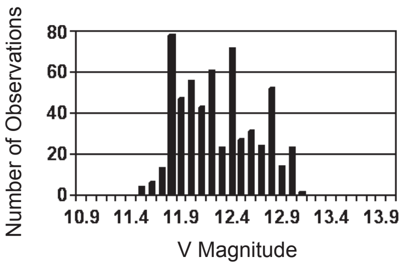

Figure 5c. 581 points.

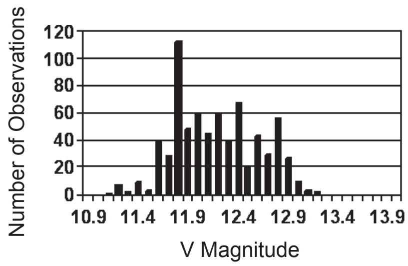

Figure 5d. 709 points.

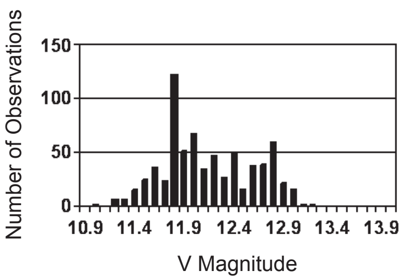

Figure 5e. 681 points.

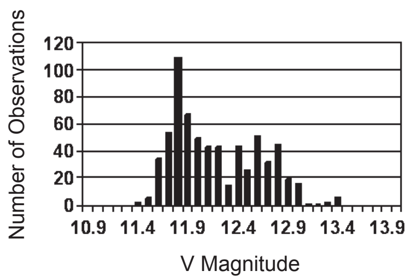

Figure 5f. 660 points.

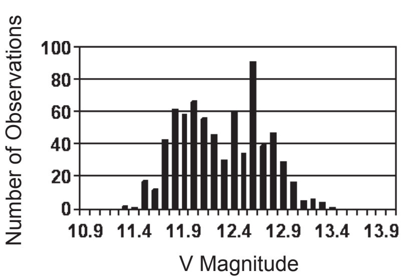

Figure 5g. 720 points.

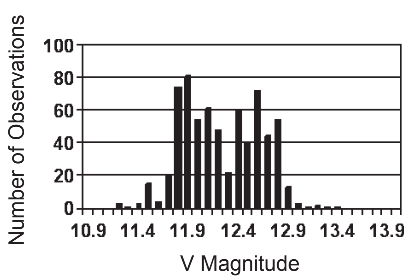

Figure 5h. 669 points.

Figures 5c–5h. Combined AAVSO and RASNZ data on V818 Sco, cont. *(See preceding page for details; Figure 5 continued on next page.)*

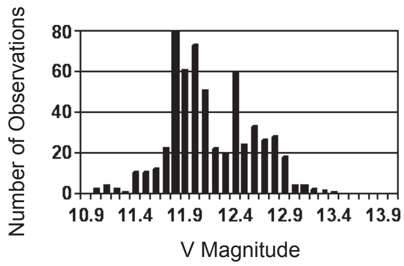

Figure 5i. 569 points.

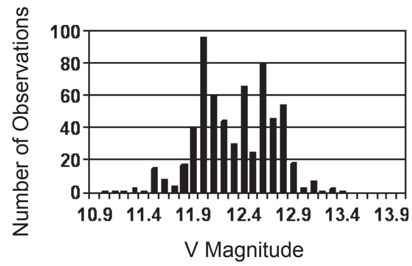

Figure 5j. 616 points.

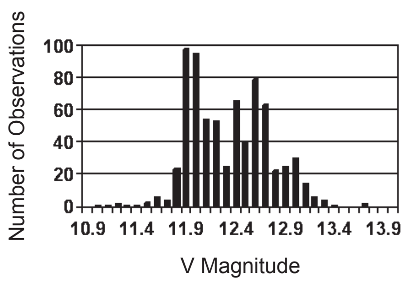

Figure 5k. 710 points.

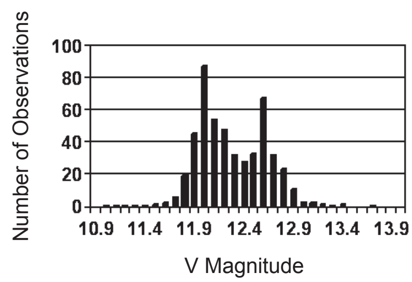

Figure 5l. 505 points.

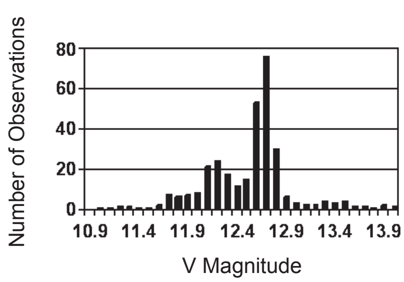

Figure 5m. 308 points.

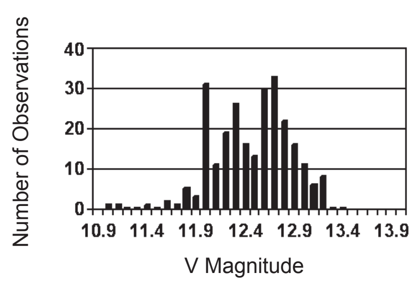

Figure 5n. 256 points.

Figures 5i–5n. Combined AAVSO and RASNZ data on V818 Sco, cont. *(See preceding page for details.)*