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Henry Norris Russell Prize Lecture of the American Astronomical Society[a)]
Fifty years of novae

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INTRODUCTORY SURVEY

When I accepted this invitation I realized that I could not hope to tell you anything that you do not know already. Ten, 20, 30, 40, 50 years ago I could have given you news. Today I can offer only a panorama.

The reward of the young scientist is the emotional thrill of being the first person in the history of the world to see something or understand something. Nothing can compare with that experience; it engenders what Thomas Huxley called the Divine Dipsomania. The reward of the old scientist is the sense of having seen a vague sketch grow into a masterly landscape. Not a finished picture, of course: a picture that is still growing in scope and detail with the application of new techniques and new skills. The old scientist cannot claim that the masterpiece is his own work. He may have roughed out part of the design, laid on a few strokes, but he has learned to accept the discoveries of others with the same delight that he experienced for his own when he was young.

When I was born, more than 75 years ago, the portrait of the nova was a mere silhouette—a sketch of changing brightness with a constant undercurrent of surprise. Novae never cease to surprise us with their sudden outbursts and unpredictable behavior. Nova T Aurigae (1891) is practically prehistoric. Its abrupt appearance was followed about three months later by an almost equally abrupt decline in brightness, and its reappearance was a surprise that would be repeated in detail 44 years later by DQ Herculis. The spectra of these novae, too, can be matched step by step. It was the turn of DQ Herculis to spring a surprise by proving to be an eclipsing star, and T Aurigae performs eclipses with nearly the same period. Such detailed similarity can hardly be accidental.

Fifty years ago there was already an impressive collection of silhouettes—records of changing brightness that displayed both pattern and variety. Some novae ran their course fast, some slowly. Four had been well observed: the very fast GK Persei (1901) and V 603 Aquilae (1918), the moderate V 476 Cygni (1920), and the slow DN Geminorum (1912); one of them is still a cornerstone of our knowledge. Two landmarks stand out. In 1890 T Pyxidis had appeared, brightened, and disappeared. When I first came to Harvard they were still telling how it was found again during a routine survey of plates taken in 1919, and how Miss Leavitt exclaimed: "That star hasn't been seen for almost thirty years!"—the first recurrent nova to be discovered. It repeated in detail the pattern of its relatively leisurely changes of brightness. So the nova process could not be regarded either as the product of an isolated accident or a final catastrophe.

More important, and often forgotten, gross differences between novae had been recognized by Lundmark, who established class distinctions among the stars, and designated by "upper-class novae" the objects that are known today by the less happy term "supernovae." But that is another story. There have been no galactic supernovae during the past fifty years, and I will not presume on my acquaintance with the stellar aristocracy.

The portrait of the nova was still in the silhouette stage when I became an astronomer, but the idea of classes of novae that differed in range and luminosity had come to stay. The recurrence of the nova phenomenon once established, a link was suggested with that group of stars with frequent and abrupt recurrences now known as the dwarf novae—the U Geminorum and Z Camelopardalis stars. The Gaposchkins were responsible, I think, for the name by which the whole group is known today. We hesitated, I remember, between the terms "catastrophic" and "cataclysmic," and decided on the latter. A catastrophe, says the dictionary, is a final event—a conclusion usually unhappy; a cataclysm is a great and general flood. I think that time has justified the choice. The nova phenomenon is probably not a final event, and certainly not an unhappy one. Undoubtedly it involves a flood of energy, perhaps gradually built up, sometimes steady, at other times abruptly released.

Even 50 years ago it was clear that novae are not rare. Often as I have analyzed the estimate of 50 galactic novae a year brighter than the seventh apparent magnitude, I cannot reduce it very much. Since 1900 there has been one classical nova per decade brighter than the third magnitude. If this has been going on for so short a time as a million years there should be a 100 000 ex-novae brighter than the 17th magnitude, provided the novae have not been recurrent. The dwarf novae, too,

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must be very numerous; nearly 300 are known, all within less than two kpc. At a very rough guess they are as frequent as ex-novae. By any such reckoning the novae, dwarf novae, ex-novae (and potential novae) together must be among the commonest of variable stars. Their occurrence can be no accident: They represent a definite and frequent stage in stellar history. Our task has been to identify this stage and put it in its context.

I. THE PHYSICAL PICTURE

The nova of 1901, GK Persei, sprang its own surprise on the astronomical world. Miss Cannon used to tell that when she saw the first photograph of its spectrum, she exclaimed that the wrong star had been observed. For it was an absorption spectrum, and until then only bright line spectra had been observed for novae. The famous spectrum is worth another look, and a comparison with that of our modern V 1500 Cygni at a similar stage; they are surprisingly similar.

With GK Persei the study of novae entered a new phase. The silhouette gave place to a detailed picture, to be elaborated in the ensuing years with extraordinary finesse. Only on the rise and at the peak of brightness can we speak of *a* spectrum, which recalls but does not exactly duplicate that of a star. The components of each are identified by a common radial velocity (not necessarily constant with time). Each bears the marks of a characteristic composition and excitation. The different spectra may coexist, overlap with, or succeed one another in bewildering variety. As a general rule, the later a spectrum appears, the higher is its excitation and the greater its radial velocity. Emission spectra appear first to accompany, and later to supersede, the absorption spectra.

I illustrate the dramatic change in our understanding of novae by a reference to the spectrum of GK Persei, 221 days after the outburst. The nebular stage was well advanced. Of the 11 strong bright lines, only five—and those the weakest—had been identified nearly a quarter of a century later as hydrogen and helium, neutral and ionized. The forbidden lines of O III were not decoded until 1925 by Bowen, and one of my most joyful memories concerns the identification of those of [Ne III] and [Ne IV] in this spectrum by Donald Menzel, Joe Boyce, and myself.

It was the work of Dean McLaughlin during the '30's and '40's that conferred some sort of order on the successive stages in the light and spectrum of novae, dissected the silhouettes and classified the portraits. In the former he recognized initial rise, premaximum halt, final rise, early decline, transition, and final decline to the postnova. His names for the successive spectral stages have provided guidelines for all later discussions: premaximum, principal, diffuse enhanced, Orion, nebular, and postnova. McLaughlin performed a great feat in producing order out of the apparent chaos, but the very success of his system should not leave the impression that all novae must necessarily be seen to pass through all these stages. The transition stage of light variation is easily identified in GK Persei and V 603 Aquilae with their rhythmic, semiperiodic changes; but when did the transition stage end for DK Lacertae and HR Delphini, and why was it not observed at all for CP Puppis, V 1500 Cygni, and RS Ophiuchi? The diffuse enhanced and Orion spectra were extremely fleeting for CP Puppis, and even more so for V 1500 Cygni.

Obviously the explosions are not all alike. The star-like spectra before maximum and at maximum run the gamut from pseudo-B stars for T Coronae Borealis and V 1500 Cygni to the K spectrum of V 1148 Sagittarii. Roughly, the greater the radial velocity of the premaximum spectrum, the earlier that spectrum is. The range in velocity and excitation at maximum is greater than the contrast in the energy of the outburst.

It was over 50 years ago that responsible ideas about the nature of the outbursts began to take shape. The naive idea that we are witnessing the birth of a star gave place to the notion of an explosion. Stratton had come to grips with the problem in 1912 in the shape of DN Geminorum. I well remember his lecture on novae at Cambridge in 1922: "The whole thing," said he, "goes phut." A few years later, Hartmann published what then, I suppose, was the shortest astronomical paper on record: "Nova Problem zerlöst—Stern zerplatzt." A commonplace now, it is hard to remember that we had not always known it.

I do not recall when I began to think of thermonuclear reactions as a source for the outbursts. I do remember a conversation with Shapley in the '40's in which I told him I was putting aside my research on novae "until the boys have finished their research on the atom." He turned to me with a blanched face. "Don't you realize," he said, "how hush-hush that work is?" Of course I did not know what was going on in the Manhattan Project, but he had his ear to the ground, while I was listening to the stars.

Nowadays the thermonuclear runaway holds the field as the source of energy for the nova outburst. We should not forget that the idea was first seriously put forward by Schatzman in 1950, another landmark in the understanding of novae, and was put into modern form by Kraft in 1963.

II. SPECTRUM, STRUCTURE, AND COMPOSITION

The spectral development of a nova is of such beautiful and fascinating complexity that it would be easy to devote not a lecture, but a lifetime, to the study of even one. The slower the nova, the smaller the velocities, the more leisurely the development, the finer is the detail and the greater the temptation. We obviously have here a gigantic laboratory for the study of the changing conditions in the expanding material. The excitation rises; the continuum declines in brightness; the density falls; and a succession of forbidden lines appears. What is happening? Can we reconstruct the explosion?

The nova of 1925, RR Pictoris, is a good example. In spite of the temptation to devote the rest of the lecture to its spectrum, I will be brief. The enormous monograph of Spencer Jones and a number of his later papers carry the published record through more than a decade. The results of the Lick Observatory series of plates have not been evaluated. I have devoted many months to study of the Harvard spectra. The trees are so dense that it is hard to see the forest.

The premaximum spectrum is an almost perfect match for the F5 Ia star ι^1 Scorpii. If a curve-of-growth analysis were made at this stage, the composition would probably appear normal. There is no record, for example, of strong cyanogen bands such as those in the absorption spectrum of DQ Herculis. Nitrogen was in fact noted by Wright as exceptionally inconspicuous. If any atom was unusually prominent, it was iron. The principal spectrum was like that of an F8 supergiant. As the bright line spectrum developed, iron was represented successively by Fe II, [Fe II], [Fe, III], [Fe IV], [Fe V], [Fe VI], and [Fe VII], the last of these attaining maximum prominence (though not, of course, maximum intensity) nine years after the outburst.

I have resisted the temptation to carry out a curve-of-growth analysis of RR Pictoris. I did in fact spend much effort on doing this for DQ Herculis, but laid it aside in the conviction that the results would be vitiated by the multiple nature of the observed spectrum and by the inevitable effects of turbulence. The products of the initial explosion clearly overlie the contributions from the object responsible for the outburst, which (in the case of DQ Herculis at least) continued to eject material for several months. I saw no way to disentangle them, and even so I did not realize (as I now do) that there may well be a difference of composition between the ejecta and the underlying star. The curve-of-growth analysis of DQ Herculis and HR Delphini by Mustel and Antipova suggests that carbon, nitrogen, and oxygen may be abnormally abundant for these novae, a conclusion that I also drew for DQ Herculis, but one that I now think must be treated with reserve. How are we to disentangle the composition of the parent system from that of the explosive ejecta?

The bright lines of RR Pictoris (both permitted and forbidden) were at the beginning relatively structureless. Their width, ±400 km/sec, corresponded to the velocity of the principal absorption. After the absorption lines had become inconspicuous, the red edge of the bright lines was first more intense than the violet edge; gradually the intensity of the edges equalized, slightly more intense than the centers. With time, the center–edge contrast increased, relatively more in the forbidden lines, and about 250 days after the outburst they were definitely castellated. As we shall see, this suggests one or more expanding rings lying nearly in the line of sight.

At minimum, RR Pictoris shows a variation of brightness with a period of 0.1450255 day which has been ascribed to eclipses. But, unless the period should be doubled, giving a light curve of W Ursae Majoris type, the variation can hardly be caused by an eclipse of star by star. We cannot be sure that the inclination is in fact near 90°, though it must be fairly high. A velocity curve would settle the question of the period. The observed expanding nebulosity shows nebulous knots, and is evidently not circular. However it does not seem to show a clear elliptical image, as the nebulae around DQ Herculis and T Aurigae are observed to do. Well observed as RR Pictoris is, a known binary system and relatively bright, it is still incompletely analyzed. A detailed study of its geometry is probably within reach.

I began with RR Pictoris because it was one of the slowest of novae, but it was not inferior in energy output to the fastest. The final level of excitation, though slowly attained, was very high. The extremely slow nova RT Serpentis reached equally high excitation. The slow recurrent nova T Pyxidis went even further: It was the first nova in which the coronal lines of [Fe X] and [Fe XIV] were observed. They were also recorded, along with other lines of very high excitation, in the spectrum of the fast recurrent nova RS Ophiuchi, and for a time were thought to be characteristic of recurrent novae. But the lines of [Fe X], and others of high excitation, were soon detected for fast novae not known to be recurrent, CP Puppis and V 1500 Cygni for example, as a result of studies in the red and infrared.

III. GEOMETRY OF THE OUTBURST

It has long been clear to everyone who looked at the developing structure within the bright lines that a nova outburst is not a spherically symmetrical expansion or explosion. McLaughlin repeatedly insisted that it always shows evidence of some kind of axial symmetry. The classical example of structural analysis is V 603 Aquilae (1918). We owe it to the observation of an expanding nebula by Barnard and to the skill and prescience of W. H. Wright, who took a series of historic spectrograms with the slit in various orientations relative to the nebula. We had known for years—it was first pointed out to me by Baade—that these spectra would permit a detailed reconstruction of the outburst. It was left for Weaver to complete the analysis more than 50 years later. The result is a model in which the ejected material is concentrated in a series of equatorially symmetrical rings or cones and two "poleward" blobs. The axis of the former is very nearly in the line of sight, the motions of the latter slightly inclined to the line of sight. Underlying the spectrum of the ejecta was the varying spectrum of the source, with a different line and velocity structure and (probably) different composition, which fluctuated semiperiodically for several weeks. The main "shell" was ejected within a very short time; its structure was already traceable in the first postmaximum spectra. *Mutatis mutandis,* this model can serve for the analysis of all nova outbursts.

No eclipses are found for V 603 Aquilae, so the line of sight is not in the plane of the orbit. The star is, however, a spectroscopic binary, so the line of sight is not perpendicular to the plane of the orbit; Warner assigns an inclination of 15°, compatible with the model just described. The accepted picture of the cataclysmic variables of short period involves a low-luminosity red star and a low-luminosity hot star surrounded by a gaseous disk with a hot spot produced by the impact of material flowing through the Lagrangian point of the red star. The disk, in this model, always lies in the plane of the orbit; indeed, if it did not do so, the consequences are hard to picture. The model pictured by Weaver shows a disk that does not lie in the orbital plane. However, the deduced geometry of the outburst merely reveals the directions in which the ring system and the polar blobs were ejected, and these may not be uniquely related to the plane of the disk. In any case they were evidently not mutually perpendicular, and the polar blobs may well have been directed to the pole of the orbit.

This beautiful reconstruction cannot be repeated until observations similar to those made by Wright are carried out for other novae, and this must depend on the observability of an expanding shell. No such shell was recorded for DN Geminorum, but there was one for CP Puppis. We must hope that V 1500 Cygni will furnish a source of such information and that it will not be neglected.

Once the ring-and-polar-blob model has been formulated, it is possible to undertake some reconstructions, even in the absence of oriented spectra. Hutchings has predicted bright line profiles for a number of cases, and has successfully interpreted HR Delphini ($i = 62°$) in terms of polar blobs and two rings; FH Serpentis ($i = 40°$) with two polar blobs, and LV Vulpeculae ($i = 50°$) with one ring and two polar blobs. The bright lines of these novae show, respectively, six, two, and four components. Boyarchuk has generalized the picture more formally: For $i = 0°$ or $90°$ the bright lines show an odd number of components; for $i = 45°$ there should be an even number, and intermediate inclinations will in general show an even number, up to a limit determined by the intrinsic widths of the bright components.

As DQ Herculis is known to eclipse, its inclination must be near 90°. Its integrated spectrum was observed by Humason and by Swings and Struve to show two main components of each bright line with a weaker one between them; an odd number of components was observed, as expected. Later observations were shown by McLaughlin to point to five components.

Odd numbers of components have also been observed for V 719 Scorpii (3), HR Lyrae (5), DN Geminorum (7), and CP Puppis (11); these novae, especially the latter, would repay analysis. A striking example of an even number of components is furnished by V 1500 Cygni, and for this star an immediate inclination has been deduced. However we should remember the periodic variations (0.13656± day). If these variations are due to eclipses, the inclination must be quite high. They recall in appearance the variations of RR Pictoris at minimum, which were mentioned earlier. True eclipses when the star is still bright are hard to interpret.

The approach to the geometry of the outburst by way of the number of components of the bright lines may, in fact, be an oversimplification. For many novae the complexity increases with time (through there are rarely changes of symmetry), and may also differ with excitation. The structure of the bright lines of GK Persei is a case in point. The spectrum taken by Humason 33 years after maximum shows that most of the ejected material then observable was red shifted and is accordingly on the far side of the system. Similar distribution is shown by the radial velocities of the components observed earlier: There seem to be six components, but a symmetrical distribution would lead us to expect nine. If, in fact, the ejection from GK Persei was one-sided, no conclusions can be drawn from the number of components. In V 603 Aquilae the violet-shifted polar blob was much weaker than that to the red. Indeed, the intensities of the components of bright lines tend to change systematically, as they did for RR Pictoris, and this is true of forbidden as well as permitted lines, so that self-absorption cannot be invoked, though circumstellar absorption may be. Conclusions should therefore be drawn with caution from observed numbers of components.

Despite these qualifications, the study of the structure of the bright lines as an index of the geometry of the outburst has opened up a rich and unexploited vein. It could be explored even with uncalibrated spectra, due attention being paid to the effects of plate sensitivity, and to the interplay of expanding "shell" and underlying star, which have neither the same line structure nor (probably) the same composition. Consider, for instance, the spectrum of CP Puppis on JD 243700. In gross structure, the bright lines show two maxima; for the hydrogen lines the red component is the stronger, but for He II 4686 the violet component is more intense. Is this a true difference, or is it occasioned by the wide flaring profile of the N III lines near 4640, which originate in an underlying object? Such differences, and the increasing complexity of line structure with time, are not yet understood.

IV. PRE- AND POSTNOVA

The development of the postnova is an old story. The absorption spectra, the accompanying emissions, and finally the nebular emissions disappear. The star seems to revert to its original brightness. Exceptions are hard to find. We must remember that only one third of the accepted classical novae have been observed at minimum. Moreover, all novae fluctuate at minimum, with a variety of ranges and on a variety of time scales from hundreds of days down to minutes. Because there are, and can be, so few preoutburst observations, a few apparent exceptions to the return to preoutburst conditions need not concern us unduly.

The reversion to premaximum brightness, fortified by the fact of recurrence, led long ago to the conviction that nothing very fundamental has happened. Attempts to evaluate the mass loss during outburst (though quantitatively uncertain) pointed the same way. It was realized that the clue to the nova lay in its condition at minimum.

In 1938 came Humason's landmark survey of the spectra of old novae, with the common feature of a blue continuum, sometimes with bright lines. Here again was a surprise: T Coronae Borealis, which Humason tended to exclude from the class on account of its M spectrum. Eight years later this star sprang another surprise: It had another maximum and moved into the recurrent nova class. Humason's instinct was right: T Coronae *was* different. But note that he saw nothing unusual about two other recurrent novae, RS Ophiuchi and T Pyxidis. We know now that the former, like T Coronae Borealis, has an M giant component.

Humason's paper focused attention on a common feature: a blue continuum sometimes with bright lines, an observation that has since been fully amplified by Greenstein. Five years later appeared a similar sketch of the dwarf novae in the landmark investigation of Elvey and Babcock. Here, again, was low luminosity, a blue continuum, with or without bright lines. We had the basis for recognizing the essential similarity of all the cataclysmic variables, the classical and dwarf novae.

V. THE NOVA AS BINARY

Another landmark, another surprise, was to follow. It was Joy who found in 1952 that the dwarf nova SS Cygni is a spectroscopic binary, and in 1954 he showed that the cognate star AE Aquarii is a double-lined spectroscopic binary, leading to the first estimate of the mass of such a system (later to be modified by a redetermination of the period). Suddenly the whole picture was unified. In 1962 Kraft brought together the information on dwarf novae, and in 1964, that on classical novae. "The presumption is," he wrote, "that all [U Geminorum stars], in fact, are close binaries of rather short period." "Membership in a certain type of close-binary system is a necessary condition for a star to become a nova." The study of cataclysmic variables had reached a plateau. We note the word "necessary;" is it in fact necessary? Is it also sufficient? These questions still exercise us a decade later.

The picture of the nova had been filled in with elaborate detail. One nova after another conformed, to a greater or less extent, to the schemes of light curve and spectral development sketched by McLaughlin. There was a growing conviction that dwarf novae and classical novae had a common structure. The silhouette had given place to a detailed portrait. There was a suggestion of perspective in the picture. Two dwarf novae had been shown to be spectroscopic binaries. The recognition of spectroscopic detail was revealing the outbursts in three dimensions.

The Gaposchkins had often discussed their dream that an eclipsing star might become a nova, thus answering the fundamental questions about mass and dimensions. What I, for one, had not expected (though I should have done so) was that a nova would prove to be an eclipsing star. I learned the news of Walker's epoch-making discovery of 1956 the hard way. I was giving a lecture on novae (*absit omen*!) when a visitor from the West interrupted me to announce that DQ Herculis had been observed to be an eclipsing star. My immediate response, I remember, was: "You're kidding!" There is the consolation that I was in good company. Miss Cannon was caught napping by GK Persei in 1901. Novae are like that. It could happen to any of us.

Twenty years later we can see what a rich vein had been opened up. Today we have four, perhaps five, eclipsing novae, six eclipsing dwarf novae, 12 eclipsing potential novae; five novae, nine dwarf novae, and eight potential novae are known spectroscopic binaries.

But our story is not yet told. The nature of the hot component is far from clear. In the beginning it was called a white dwarf, but if it is a white dwarf, it must be something else as well. Dimensions and masses still present thorny problems. And we have not yet answered the question: Is such a binary system necessary, and is it sufficient?

Necessary it certainly is not. We recall the red giant component of T Coronae Borealis; other recurrent novae have giant companions, and they are not all M stars. The slow nova RR Telescopii, the only nova extensively studied before its outburst, has an M5 III component. And the Z Andromedae stars, which I shall mention later, and which must be novae of a sort, have red giant components.

The condition may not be sufficient, either. The short-period binary V 471 Tauri consists of a white dwarf and a K0 V star. Is it a nova or a potential nova? It undergoes no rapid intrinsic variations, but it has a very odd light curve. Its half-day period is longer than those of most cataclysmic variables, but those of GK Persei and V Sagittae are equally long.

There are, of course, a great many binary systems, most of them of very long period, that contain a white dwarf and are not known to share the properties of the cataclysmic variables. But there is always the system of Mira Ceti, with its blue dwarf component VZ Ceti, which strongly recalls a potential nova, as will be discussed later.

Is a nova necessarily even a binary? It seems (to express a personal opinion) that the existing evidence points in that direction, though other suggestions have been made. It is notoriously difficult to "prove a negative." However, I think that binaries that are not novae present a more intriguing problem than novae that are not binaries.

VI. PROPERTIES OF THE CATACLYSMIC BINARY

This is the heyday of the cataclysmic binary. There are currently two discussions of their properties, by

TABLE I. Cataclysmic binaries of known period.

Name	Period	Type	Binary	Max.	Min.	Bright lines H	He I	He II	4650	Other	Cycle	Mass Blue	Red	Spectrum
AM CVn	0.01216	PN	ecl.	13.94	13.98		w							DBp
WZ Sge	0.056688	UG?	ecl., sb.	7.0	15.5	s	w				33^y	>1.5	0.12	Be
V436 Cen	0.064028	UG	ecl.	11.9	15.4	vs, d?	w				25^d			
EX Hya	0.06823	UG	ecl., sb.	11.4	14.1	s, d	s	w		Ca II	465	>1.07	0.16	
VV Pup	0.06975	PN	ecl., sb.	14.6	17.1	s	s	w						Pec
VW Hyi	0.074271	UG	(ecl.)	8.5	13.4	vs, d					28			
Z Cha	0.074502	UG	ecl.	12.	13.5	s, d					96			
AN UMa	0.0796894	PN	ecl.	13.8	14.4	s	s	s						
MV Lyr	0.08::	PN		10.5	14.0	s	w							Op
AM Her	0.128819	PN?		12.4	14.2									
V1500 Cyg	0.13656	Na	ecl?	2.2	20									
TT Ari	0.1375	PN	ecl., sb.	10.2	11.8	w	abs.	vw	vw			0.79	0.38	B
V603 Aql	0.138542	Na	sb	−1.1	12.8	w	w	s	w			0.87	0.40	Be
VZ Scl	0.1446222	PN	ecl., sb.	15.6	18.1	s	s	s				0.32:	0.44	Be
RR Pic	0.1450255	Nb	ecl.?	1.2	12.8	w		s	m					
WX Hyi	0.14989:	UG		9.6	14.7	w								
WW Cet	0.159722	UG	sb.	9.3	16.3	s	m	m		Ca II m				
U Gem	0.176906	UG	ecl., sb.	8.8	14.2	s, d	w	w		Ca II s, d	105	0.92	0.53	Be
SS Aur	0.180556	UG	sb	10.5	14.8	s	w			Ca II s	54	0.89	0.57	Be + ?
HR Del	0.1913515	Nb	sb											cont.
DQ Her	0.1913515	Nb	sb	1.3	15	s	s	vw	s			1.09	0.58	Be
UX UMa	0.19667128	PN	ecl., sb.	12.7	13.8	w		s	vw	Ca II abs?				O
T Aur	0.2043786	Nb	ecl.	4.1	15.8	w	w							
RX And	0.21173	Z Cam	sb.	10.3	13.6	s	w	m		Ca II m	14	1.02	0.65	Be
RW Tri	0.23188	PN	ecl., sb.	13.5	16.04	s		s		Ca II abs.				
GP Com	0.261	ZZ	sb?	15.69	15.9									dB
SS Cyg	0.276	UG	sb.	8.2	12.1	s	s			d	52	0.80	0.89	Be + dG5
Z Cam	0.2878	Z Cam	ecl., sb.	10.2	14.6	s, d	s			m	20	1.26	0.90	Be + G?
EM Cyg	0.290909	PN	ecl., sb.	11.9	14.4	s, d	w	w			22	0.73	0.95	+ G–K
RU Peg	0.370833	UG	sb.	9.0	13.1	s, d	m			d	66	1.02	1.20	Be + G8 IVn
AE Aqr	0.4116550	Z Cam?	sb.	10.4	12.0	s				Ca II		1.25	1.18	Be + K2 V
V Sge	0.514195	PN	ecl., sb.	9.5	13.9	hazy	hazy							WN5 + d G
V471 Tau	0.521193	?	ecl.	9.40	9.71									K0 V + D
BV Cen	0.609714	UG	ecl.	10.5	14.2	s, d	d				99			+ dG
GK Per	0.684722	Na	sb.	0.2	14.0	s	s	m		Ca II				Be + K2 IV
V818 Sco	0.787313	PN	ecl.? sb.	11.1	14.1	s	s	w	w	Fe II, O II				Be

Robinson and by Warner, that cover the subject so fully that it would be an impertinence to compete with them. I shall repeat five general statements that are so well known as to be commonplace, and remark not on their validity, which is well established, but on some questions that they raise.

(a) *The orbital motions favor the shortest periods, but are not confined to them.* We compare the frequency of known periods of cataclysmic variables (both eclipsing and spectroscopic binaries) with that of the known W Ursae Majoris stars. Even though we limit ourselves to periods under a day, we see that the cataclysmic variables, though crowded towards the short periods, are not confined to them. The fast nova GK Persei and the x-ray nova V 818 Scorpii are on the long side of the frequency maximum for W Ursae Majoris stars, near a third of a day. And if we include the Z Andromedae stars with the cataclysmic variables, as I think we must, there are many with periods of hundreds of days as well. Of these I shall say a word later.

There are 54 W Ursae Majoris stars with periods less than three-tenths of a day (I exclude cataclysmic variables). In searching these for potential novae, we can probably eliminate those that show an integrated spectrum of late type (such as AD Cancri, XY Leonis, BX Pegasi, and VZ Piscium), especially as they have primary and secondary minima of equal or nearly equal depth, for we are looking for binaries with one blue

TABLE II. Symbiotic cataclysmic binaries of known period.

Star	Orbital period	Type	Binary	Range	Mass Blue	Mass Red	Spectrum
T CrB	227.6	Nr	sb.	2.0–10.8	1.6:	2.1:	Be + gM3
AX Mon	232.5	?	sb.	6.59–6.87			Ble + K0 III
RW Hya	376	Z And	sb.	10.0–12.7	1:		gMep + B
AR Pav	605	EA, PN?	ecl.	10.0–12.7	0.9	0.7	Be + cF + M
R Aqr	730?	Mira, PN?	sb.	5.8–11.5	<1		M5e–8e + B2e
BF Cyg	750	Z And	sb.	9.3–13.4	~1		Be + gM4
CI Cyg	815	Z And	sb., ecl.	10.7–13.1	~1		Be + gM4
AG Peg	830.14	Z And	sb.		to 1.5	<6	WN6 + M1–3 II–III

component. On the basis of their short periods, V 523 Cassiopeiae, BF Pavonis, EQ Tauri, and AB Telescopii might be worth examining for the erratic short-term variations that are characteristic of quiescent cataclysmic variables.

I began with the W Ursae Majoris stars because they have often been mentioned as possible ancestors for cataclysmic variables. Is it quite certain, however, that we should look for cataclysmic variables only among the W Ursae Majoris stars? The first eclipsing nova to be discovered had an Algol-type light curve, and would have been classed as an Algol star if its outburst had not been recorded. A comparison of the eclipsing light curves of DQ Herculis, UX Ursae Majoris, and U Geminorum shows that they are of similar type; even the bizarre variation of U Geminorum would not have placed it in the W Ursae Majoris class. The hump for UX Ursae Majoris is, in fact, more pronounced than that of DQ Herculis. Another dwarf nova with an Algol-type light curve is Z Chamaeleontis.

There are four stars cataloged as Algol variables with periods less than three-tenths of a day, and three of them (VZ Sculptoris, RW Trianguli, and UX Ursae Majoris) are recognized cataclysmic variables. The fourth, V 1961 Sagittarii (period 0.2038504 day) is bright enough for intensive study. When we recall that GK Persei, for example, has an orbital period well over half a day, it seems that all short-period Algol stars are worth examination; I suggest UX Canum Venaticorum, UU Lyncis, and DD Scuti.

There are, of course, eclipsing cataclysmic variables, such as WZ Sagittae, that have W Ursae Majoris light curves. However, it seems that the ancestors of cataclysmic variables need not be sought only among the W Ursae Majoris stars, but rather among all binaries of short period. Novae and dwarf novae are not contact binaries of the conventional sort. On the other hand, all the binaries of very short period are not now cataclysmic variables.

Both W Ursae Majoris itself and the Algol star U Cephei have been observed to undergo modest irregular outbursts, and the gaseous rings associated with the blue component of RW Aurigae may suggest a disk in the making.

(b) *All the systems include a low-luminosity blue star, and the spectrum of a star of late spectral class is observable for those with orbital periods greater than a quarter of a day.* The limits of visibility of the red component are readily understood if all these secondaries are main-sequence stars.

The star of shortest period in my list that shows the spectrum of a red component is SS Cygni (period 0.276 day), and most of those with greater orbital periods do so. An exception seemed to be BV Centauri, with a published period of 0.1580 day; but Warner, citing Feast and N. Vogt, gives 0.609714 day and mentions dG absorption. Scorpius X-1 = V 818 Scorpii has no recorded secondary spectrum. Also GP Comae (classed as a ZZ Ceti star, a variable white dwarf, and possible spectroscopic binary with period 0.261 day) has no observed secondary. It shows rapid erratic changes of brightness.

The blue components show one of the few systematic differences that can be discerned between classical and dwarf novae: As Warner points out, their bright line spectra, when observed, show somewhat higher excitation for the classical novae. For the potential novae, high and low excitation seem to be equally distributed.

The late-type companions fall into two groups. Those with orbital periods less than a day are of low luminosity, probably main-sequence stars (though with surface conditions modified by the presence of the other component, so that luminosity class may differ with presentation). Those with long orbital periods are primarily of luminosity class III; most of the known ones are M stars, but the secondary of V 1017 Sagittarrii is of class G5 III. Three recurrent novae (T Coronae Borealis, RS Ophiuchi, and V 1017 Sagittarii) have giant secondaries, and it is tempting to conclude that recurrence is related to this fact. But no giant secondary is recorded for T Pyxidis, and it is not red at minimum, which seems to rule out an M star. It might, perhaps, have a secondary like that of V 1017 Sagittarii; an observation of its minimal spectrum is greatly to be desired. If WZ Sagittae is to be included with the recurrent novae, it cannot have a giant secondary; there is no room for it with so short a period. Warner has placed it with the dwarf novae, in spite of its 33-yr cycle which sets it apart from other members of the class.

Beginning with T Coronae Borealis, I have tabulated eight stars that are undoubtedly cataclysmic. All have secondaries that are late-type giants. Four are "symbiotic variables," one a peculiar eclipsing star (AR Pavonis), and one is a Mira star (R Aquarii). The associated orbital periods are all long, between 200 and 800 days. Five are double-lined spectroscopic binaries, and, in each case,

TABLE III. Symbiotic binaries of unknown period.

Star	Range	Spectrum	Period intrinsic (days)	Period orbital (days)
Z And	8.0–12.4	M2 III + Be	694	...
R Aqr	5.8–11.5	M5e–8.5e + B2e	386.92	730?
TX CVn	9.3–11.6	K2 + B5e	...	...
RT Car	11.0–11.4	M2 Ia + OB?	...	...
YY Her	11.7–13.2	M2e + O	...	...
V443 Her	12.39–12.63	M2e + O	...	...
RS Oph	5.2–12.3	Ocp + M2 ep	...	...
AX Per	10.8–13.0	gM3e + hot star	685	600–800?
V1017 Sgr	6.2–14.4	G5 IIIep + hot spot	...	...
V2905 Sgr	10.0–14.6	Beq? + M?	...	...
RR Tel	6.5–16.5	M5 III + hot star	386.73	...

the M star has evidently two or three times the mass of the blue star, which has accordingly about $1 M_\odot$.

Of the eight symbiotic stars listed, one (T Coronae Borealis) is a nova by any definition. The expanding nebula of R Aquarii points to a violent event several hundred years ago, and the surge of 1921, accompanied by suppression of the long-period variation, is well known. There have been cataclysmic outbursts by RW Hydrae, BF Cygni, CI Cygni, and AG Pegasi. The blue component of AR Pavonis must be responsible for its persistent variation on a time scale of hundreds of days, as well as shorter fluctuations. For all these stars it seems likely that (despite the long periods and large scale of the systems) interaction with the giant component is related to their behavior. I should like to see photometric study on a short time scale.

I have listed only systems for which an orbital period seems well established, following Boyarchuk's results for the stars he has discussed. For R Aquarii the figures are uncertain. The published radial velocities are scattered and are confused by the inclusion of dates during the recent outburst; a determination of the period during an undisturbed interval would be valuable.

A number of other "symbiotic" stars are clearly of the same kind, notably Z Andromedae, and AX Persei, which undergo cyclic nova-like outbursts; their orbital periods would repay investigation. I was originally attracted to Z Andromedae by Harry Plaskett's detailed study of its complex spectrum, and was struck by the fact that his paper did not mention the star's violent variability, which is the key to its behavior.

When considering the symbiotic variables, we should not forget Mira Ceti, whose companion, VZ Ceti, varies through 2.5 mag, with rare short flares. This binary has a period of about a century, and masses of the order of the solar mass. Even at the great distance involved, there is evidently interaction between the red variable star and its cataclysmic companion.

I have carefully called the primaries of all these systems blue stars of low luminosity. To call them white dwarfs is an oversimplification; they are degenerate objects, but also something more. Their masses and luminosities are not incompatible with their being white dwarfs, but their measured gamma velocities are not sensibly different from those of their red secondaries.

(c) *The orbital period is not correlated with the range of the outburst.* It seems to be established that the orbital period is correlated with the size of the secondary, that the latter is a main-sequence star (for periods less than a day), and that therefore the period is correlated with its luminosity and its mass. But surprisingly, these properties are not correlated with the nature of the outburst. Classical novae have both short and long orbital periods. Dwarf novae have orbital periods from 0.055588 day for WZ Sagittae to 0.4116550 day for AE Aquarii; those of potential novae range from 0.01216 day for AM Canum Venaticorum to 0.514195 day for V Sagittae.

There is a lack of correlation between orbital period and velocity of ejection for classical novae; I have selected the principal absorption for comparison (Table IV).

(d) *The orbital period is unrelated to the outburst cycle.* The fact that novae, whose outburst cycles (if any) must be reckoned at least in centuries, have periods distributed throughout the observed range, shows that there is no relationship on a gross scale. Within the dwarf novae, also, there is no relationship. Potential novae, with no obvious outburst cycle, are also distributed throughout the whole range of orbital periods. It is true that no classical nova has an orbital period less than 0.1 day unless we include WZ Sagittae, which I have fol-

TABLE IV. Orbital period and expansion velocity.

Star	Period (days)	Velocity (km/sec)	Star	Period (days)	Velocity (km/sec)
V 1500 Cyg	0.13656	−1700	DQ Her	0.1936270	−350
V 603 Aql	0.138542	−1700	T Aur	0.2043786	−400:
RR Pic	0.1450255	−350	GK Per	0.684722	−1400
HR Del	0.1913515	−600	T CrB	227.6	−1350

lowed Warner in relegating to the dwarf novae.

(e) *Brightness varies on many time scales, which are unrelated to the orbital period.*

(1) The main outburst, if any, is always more abrupt at the beginning, but even then it is not always equally rapid. Apart from the well-known premaximum halt, there can be significant increases of luminosity months or years before the main brightening (V 533 Herculis, LV Vulpeculae). There may be enhanced activity just before the outburst (V 446 Herculis, T Coronae Borealis), even followed by a preliminary drop in brightness (T Coronae Borealis). The rise of RT Serpentis seems to have been very slow indeed.

There is great variety, also, in the speed of photometric development, from the very rapid rise and fall of T Coronae Borealis and U Scorpii to the slow fall of DN Geminorum and the still slower decline of RR Pictoris and RR Telescopii. The decline in brightness ranges from smooth and steady, as with CP Puppis, RS Ophiuchi, and V 1500 Cygni, though semiperiodic fluctuations on a scale of days like those of GK Persei and V 603 Aquilae, to the erratic decline of DK Lacertae. The DQ Herculis type, with its long maximum, abrupt decline, and subsequent rise, has been shown by several novae. Recurrent novae appear to repeat their maximal variations with fair fidelity.

The dwarf novae, also, show considerable variety in form of outburst, and even the U Geminorum stars are less repetitive than the recurrent novae at successive maxima. The Z Camelopardalis stars are still less repetitive, and may fluctuate at an intermediate brightness for long intervals. Finally the potential novae have no recorded main outburst. The source of the main outburst is complex: Primarily it arises from the material ejected or puffed up, but the rhythmic and erratic changes during the decline stem at least partly from the underlying object—the blue star and the associated disk and hot spot.

(2) Irregular changes of brightness at minimum on a scale of hundreds of days. Such are the variations of GK Persei and other novae, all of which probably undergo them to some extent. They presumably stem from the disk.

(3) Irregular flickering on a scale of hours and minutes; this probably stems from the hot spot.

(4) Changes associated with an eclipse of the blue star, the disk, the hot spot, or a combination of these. Such changes are of course related to the orbital period.

(5) Rapid coherent variations on a scale of seconds, sometimes continuous as with DQ Herculis, often associated with times of outburst. The characteristic periods are the strongest evidence that a white dwarf underlies the complex structure of the primary, but clearly these variations involve the whole disk in some way.

VII. THE MODEL

It would be good to be able to say that these phenomena, and the fine detail contributed by the accompanying spectroscopic changes, add up to the final portrait of the nova—a portrait in the round. But "final" and "definitive" are famous last words. Better to say "the contemporary portrait of a nova." For there is no such thing as *the* nova; all novae are different. The aficionado, confronted with a light curve or spectrum, can usually place it. We can point to detailed physical pictures of a number of novae, from quiescence to outburst and beyond. The pictures have enough in common to have permitted the construction of a model, and the formulation of some theories that relate model to behavior.

The art of nova portraiture has recently been carried to the extreme by the astronomical counterparts of Pygmalion (an Ovidian, not a Shavian Pygmalion). The image of Galatea has been wrought of the most refractory and rebellious of materials. Is she coming to life before our eyes? Will the model not only resemble, but *be,* the original? We are on the verge of knowing; the artists are now applying the final touches.

I began by looking backward; let me end by looking forward. I have spoken of many things we do not know, named many stars that I think would throw light on what is still obscure. I will not apologize for that. Even if they do not give the information I hope for, they will contribute to enlightenment. Otto Struve used to say that if you select stars at random, one in five will be remarkable. So if you press forward with the observations, the next 50 years of novae will be at least as full of surprises as the last.