Evolution of stellar systems
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THE NOVA HOLE FILLED BY X-RAY SOURCES
IN THE CENTRE OF M31

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SUMMARY

The cluster of X-ray sources within 400 pc from the centre of M31 is found to coincide with a hole in the distribution of novae. This coincidence immediately excludes capture of neutron stars by other stars as a formation mechanism for the X-ray sources: since white dwarfs would be captured more frequently due to their larger number density, this would lead to an over abundance of novae.

The most plausible explanation for the nova hole filled by X-ray sources appears to be that it is an age effect: the central region of M31 is essentially so old that its novae have already evolved beyond the nova stage. That fraction of them in which the white dwarf has collapsed into a neutron star then accounts for the presently observed cluster of X-ray sources.

Key words: novae- X-ray sources- binary stars- M31
1. INTRODUCTION

The 18 X-ray point sources detected with the Einstein Observatory within 2\' of the nucleus of M31 (van Speybroeck et al., 1979) represent an overabundance of a factor 6 with respect to the number of bulge sources located in a region of equal size around the Galactic centre. The sources in M31 were classified as bulge sources by van Speybroeck et al. on the basis of both their location and their average X-ray luminosity which is typically a factor 2 higher than that of X-ray sources associated with population I.

We point out in this paper that the central bulge X-ray sources in M31 fall just in the "nova hole", i.e. the hole in the distribution of novae in the core of M31 (Rosino, 1973). This, together with the smooth fit of their spatial distributions, seems to suggest that the two types of objects may be closely related. Various possibilities to explain such a relation are examined.

2. THE OBSERVATIONS

Fig. 1 shows the distribution of X-ray sources and novae in a region of 3\' x 2\' centered on the nucleus of M31. While 40 of the 90 nova events detected in M31 during the 15 years continuous survey by Rosino (1964, 1973) are found within 5\' from the centre, only 2 of them are found within 1\' from the centre. However, about 9 novae would be expected within 1\' on the basis of the ratio of the masses within 1\' to 5\' and within 1\' respectively (using the mass distribution of an isothermal sphere). Since the central region of M31 has received special attention in Rosino's investigation, the deficiency of novae within 1\' by a factor 4.5 is both real and significant.
The lack of novae is compensated for by 12 X-ray sources located within 1'. Because the lifetimes of novae and bulge X-ray sources may be different the similar order of magnitude of their numbers is probably a chance coincidence. However, the fact remains that the bulge X-ray sources fall precisely into the nova hole, which suggests a relation between these two types of objects.

Fig. 2 shows the surface number density distribution of novae, together with the surface brightness distribution (de Vaucouleurs, 1958). The novae follow the surface brightness profile remarkably well in the range between 2' and 9' from the centre. The nova hole clearly stands out.

3. INTERPRETATION

3.1 The origin of novae and bulge X-ray sources

The existence of the nova hole by itself means either that nova binaries do not exist (any longer) in the inner bulge of M31, or that the nova stage lasts much shorter there than anywhere else in that galaxy. The fact that the X-ray sources apparently compensate for this lack of novae strongly suggests that the novae or their progenitors may have turned into X-ray sources.

Both novae and galactic bulge X-ray sources are binary systems consisting of a compact object and a low mass star, presumably on the main-sequence. In nova systems the compact object is a white dwarf, while a variety of arguments indicate that in the galactic bulge X-ray sources it is a neutron star (Van Paradijs, 1978; Lewin and Joss, 1980).
Nova-like binaries are generally believed to originate from wide binary systems through spiralling-in of a main-sequence dwarf into the envelope of a red giant with a degenerate core. The initial separation required for such evolution is several AU (Paczynski, 1976; Ritter, 1976). The same scenario probably holds for the bulge X-ray sources in both our Galaxy and M31. The formation of these systems by capture in regions of high stellar densities—a mechanism proposed by Sutanyo (1975) and Fabian et al. (1975) to explain the occurrence of X-ray sources in globular clusters—seems excluded for the following reason. Because of the high stellar velocity dispersion prevailing in galactic bulges, the kinetic energy to be dissipated by tidal effects during a close encounter between a compact object and a normal star is so high that, if the normal star would succeed in dissipating this energy, this leads to its complete disruption (cf. Finzi, 1978). Hence no binary would be left. Thus novae as well as bulge X-ray sources most probably have originated from primordial binary system. It is then very unlikely that hardly any binary progenitors of novae were formed in the inner bulge of M31, since in this case no bulge X-ray sources would be expected either.

3.2 The nature of the bulge X-ray sources in M31

3.2.1 Soft X-ray sources

If the nova hole filled by X-ray sources in M31 is a general phenomenon in the centres of spiral galaxies, the most straightforward explanation for the fact that no equivalent of the M31 sources has been found near the centre of our own Galaxy would be that of these sources have spectra too soft to be detected, i.e. they fall below the 2 keV interstellar absorption cut-off. Van Speybroeck et al. (1979) estimate a temperature of 5 keV from the integrated
emission of the central region of M31 detected with the Einstein IPC. This result is highly uncertain as the IPC energy band was reduced to the narrow range of 0.35 - 2.9 keV during these observations, and a much lower temperature, corresponding to soft X-rays (< 2 keV), cannot be excluded. Since in all known cases accretion onto a neutron star produces hard X-rays, the compact object in soft X-ray binaries should be a white dwarf, as in nova-like systems.

That white dwarf binaries would turn into soft X-ray sources instead of become novae could be due to relatively high accretion rates (as compared to the value of $10^{-9} M_\odot \text{yr}^{-1}$ inferred for novae (Warner, 1976)) resulting in stable, rather than recurrent explosive, nuclear hydrogen burning on the surface of the white dwarf (DeGregoria, 1974; Kylafis and Lamb, 1979).

If hydrogen is burnt at the same rate at which it is accreted, the energy released by nuclear burning exceeds the energy liberated by accretion by a factor

$$f = \frac{0.007 Xc^2}{GM/R} = 47 \frac{X(M)}{M_\odot}^{-1} R_9 \ ,$$

where $X$ is the mass fraction of hydrogen, $M$ is the mass of the white dwarf, and $R_9$ is its radius in units of $10^9$ cm. The sum of the nuclear burning and the accretion luminosities is limited by the Eddington luminosity: this corresponds to a critical accretion rate

$$M_{cr} = \frac{L_{edd}}{(1+f)GM/R} = 3.0 \times 10^{-5} \frac{R_9}{(1+X)(1+f)} M_\odot \text{yr}^{-1} \ ,$$

where it has been assumed that the opacity is due to electron scattering.

For white dwarfs of about one solar mass the Eddington luminosity is $10^{38}$ erg s$^{-1}$,
so that in the case of stable hydrogen burning an accretion rate \( \dot{M} \approx 1.5 \times 10^{-7} \) \( M_\odot \) yr\(^{-1} \) would be sufficient to explain the observed luminosities of the M31 sources (\( L_x \approx \frac{1}{2} L_{\text{edd}} \)) if all the energy is emitted in soft X-rays. This falls precisely in the range of accretion rates for which Paczynski and Zytkow (1978) obtained stable hydrogen burning in their evolutionary models of a spherically accreting 0.8 \( M_\odot \) white dwarf.

For spherical accretion, as might result from mass transfer produced by a self-excited wind (Davidson and Ostriker, 1973; Arons, 1973), the soft X-radiation emitted by the nuclear hydrogen burning layer is either cooled by electron scattering or attenuated by photo-electric absorption during its passage through the cooler accreting matter, depending on whether this gas is ionized or not. The number density of hydrogen ions/atoms at a radial distance \( r \) above the surface of the white dwarf is given by (Fabian et al., 1976)

\[
n_H = \frac{(1+X)\dot{M}}{8 \pi m^2 r^2 (2GM/r)^{1/2}} = 5 \times 10^{14} \left( \frac{\dot{M}}{1.5 \times 10^{-7} M_\odot \text{ yr}^{-1}} \right) \left( \frac{M}{M_\odot} \right) \left( \frac{r_9}{R} \right)^{-3/2} \text{ cm}^{-3},
\]

with \( m \) the proton mass and \( r_9 \) the distance in units of \( 10^9 \) cm. Their column density is

\[
N_H = 2.3 \times 10^{23} \left( \frac{\dot{M}}{1.5 \times 10^{-7} M_\odot \text{ yr}^{-1}} \right) \left( \frac{M}{M_\odot} \right)^{-1} \left( \frac{r_9}{R} \right)^{-1} \text{ cm}^{-2}.
\]

At such high densities a very small HII region is formed, with a Strömgren radius of the order of the radius of the white dwarf, so that most of the accreting matter is neutral (Tarter and Salpeter, 1969). Photo-electric absorption then attenuates the radiation intensity of photons with energy \( E \) by a factor \( \exp(-\sigma(E)N_H) \). For energies (in keV) \( 0.1 < E < 0.53 \) and \( 0.53 < E < 5 \) one has \( \sigma(E) = 0.65 \times 10^{-22} E^{-3} \) and \( 2.0 \times 10^{-22} E^{-2.5} \text{ cm}^2 \) (H atom)\(^{-1} \).
respectively, in the case of cosmic abundances (cf. Tanaka and Bleeker, 1977). Hence for the column density given above no photons with $E < 5$ keV can escape if the abundances are cosmic. Soft X-ray photons escape only if the abundances of heavy elements in the wind is one to two orders of magnitude below that of the sun (cf. Davidson and Ostriker, 1974). The overall metal abundance in the central region of M31 is solar or higher, and probably at most a few percent of the stellar population is very metal poor (O'Connell, 1976); hence, spherical accretion must be discarded. The remaining possibility is mass transfer by Roche lobe overflow as in nova systems, in which case an accretion disk forms and soft X-rays can freely escape in directions perpendicular to the disk. The mass transfer rate should then be well below the Eddington limit since otherwise the binary system would be embedded in an opaque cloud.

We note, however, that not even a single stellar soft X-ray source with a strength exceeding $10^{35}$ erg/s has been detected in the Galaxy. Moreover, nova outbursts are observed to take place even for mass accretion rates in excess of $10^{-7} M_\odot$/yr. For instance, two novae in M31 have been found to be recurrent after 2 and 5 years respectively (Rosino, 1973). The luminosity curves of these novae show a maximum $M_V = -8 m$ during 100 days, i.e. a total energy output of $5 \times 10^{45}$ ergs. This corresponds to the fusion of $4 \times 10^{-7} M_\odot$, and therefore to a mass transfer rate of $2 \times 10^{-7}$ and $0.8 \times 10^{-7} M_\odot$/yr for a recurrence after 2 and 5 years, respectively, in the case of 100% efficiency. This amount of material can easily escape from the surface of the white dwarf, the required energy being only $10^{43}$ ergs for an escape velocity of about 4000 km/s.

We conclude that, both theoretically and observationally, the possibility for the existence of strong stellar soft X-ray sources is highly doubtful.
3.2.2 Hard X-ray sources

If the central X-ray sources of M31 turn out to be hard, they would present evidence for a fundamental difference between the inner parts of M31 and our Galaxy. In this case neutron stars are involved instead of white dwarfs because the observed hard X-ray luminosities of $10^{37} - 10^{38}$ erg/s are unlikely for the latter (cf. section 3.2.1).

Bulge X-ray sources are likely to belong to an old stellar population. Therefore they cannot be massive binaries. There are strong indications in the Galaxy that they are low-mass binaries containing neutron stars (Van Paradijs 1978; Lewin and Joss, 1980). We now consider how such systems can have been formed and how they are related to novae.

Recent studies (Miyaji et al., 1980; Canal et al., 1980) suggest that accreting white dwarfs in nova-like systems can be converted into neutron stars through an electron-capture supernova explosion. The conditions are:

1. The white dwarf is composed of either O-Ne-Mg, or of C-O. In the former case it results from a main-sequence star with mass in the range $8 - 12 M_\odot$, in the latter case its progenitor had a mass of $4 - 8 M_\odot$.
2. In the case of a C-O white dwarf the mass should already be close to the Chandrasekhar limit.
3. The accretion rate should be smaller than about $1.5 \times 10^{-7} M_\odot/\text{yr}$, since otherwise the outer envelope of the white dwarf expands to a red giant size.

Single white dwarfs tend to have masses in the range $0.46 - 0.70 M_\odot$ (Koester et al., 1970). The larger masses of the white dwarfs in nova systems (Robinson, 1976), i.e. close to or exceeding one solar mass, indicate indeed a composition of C-O or O-Ne-Mg rather than He. The third condition is necessarily satisfied in nova binaries. We conclude that at least a
fraction of the white dwarfs in nova binaries may become neutron stars. As very little matter is expelled, the supernova explosion is expected to be fairly quiescent (Canal and Schatzman, 1976; cf. van den Heuvel, 1977) and perhaps even unobservable, and the binary system remains bound.

Another possibility for an accreting C-O white dwarf is to undergo a carbon deflagration explosion, in which case the star will be totally disrupted. These supernova explosions are likely to be identified with the observed type I explosions (Sugimoto and Nomoto, 1980; Chevalier, 1980). Therefore the following two facts are worth noticing:

(1) The historical type I supernova observed in 1604 by Kepler, the only one located in the bulge of the Galaxy, is situated 1200 pc above the galactic plane, implying that it belongs to a very old population (cf. Tamman, 1977).

(2) The only supernova ever observed in M31, in 1885, is of type I and lies 20'' south west of the nucleus, i.e. well inside the nova hole. Hence, both these supernova may well be related to an accretion induced explosion of an old white dwarf in a nova-like system.

In conclusion both bulge X-ray sources and type I supernovae may be the end products of nova evolution.

3.3 Special conditions in the bulge of M31

We must also consider which conditions particular to the inner bulge of M31 might cause the existence of the nova hole filled by X-ray sources. If the bulge X-ray sources are the products of the long-term evolution of nova binaries, the inner region of M31 should be in a more advanced stage of evolution than the other parts of this galaxy, i.e. either its population
must be older, or the evolution of binaries must have been somewhat accelerated.

The central regions of spiral galaxies are characterized by a metal-rich stellar population, and by high stellar densities and velocity dispersions which may lead to stellar dynamical effects. Metal abundance is not found to have an important effect on the long-term (nuclear) evolution of nova systems (Savonije, private communication). Since stellar encounters do play an important role in the evolution of globular clusters and their binaries, we consider their possible effects in some detail.

3.3.1 Stellar encounters

The effect of stellar encounters depends on both the stellar velocity dispersion and the local density. The observed velocity dispersions in the bulge of M31 range from 100 to 200 km/s. We adopt here $\sigma = 150$ km/s as a reasonable mean value. Equating the mean kinetic energy of the field stars to the binding energy of a binary system we obtain a critical value for the binary separation

$$a_{cr} = \frac{GM}{\sigma^2} = 8.5 \left( \frac{M}{M_\odot} \right) \left( \frac{\sigma}{150 \text{ km/s}} \right)^2 R_\odot,$$  \hspace{1cm} (5)

where the mean mass of the field stars and the mass of each binary component have all been set equal to $M$. Binaries with separations larger than the critical value are soft, while those with smaller separations are hard. As shown theoretically by Heggie (1975) and verified with numerical experiments by Hills (1975), stellar encounters cause soft binaries to become softer and hard binaries to become harder. The progenitor systems of novae having separations of several AU (cf section 3.1) are soft, and may therefore be subject
to disruption. At a distance of 1', or 200 pc, from the centre of M31 the stellar mass density $\rho$ is about $25 M_\odot pc^{-3}$ (Oort, 1977) so that the disruption time scale there is (Heggie, 1975)

$$\tau_d = 2 \times 10^{13} \left( \frac{\rho}{25 M_\odot pc^{-3}} \right)^{-1} \left( \frac{\dot{\rho}}{150 \text{ km/s}} \right)^{-1} \left( \frac{a}{2 \text{ AU}} \right)^{-1} \text{ yrs.} \quad (6)$$

The time required to increase the initial binary separation by a factor 2 is about 2 times smaller than $\tau_d$. Clearly, significant widening or disruption of nova progenitors can take place only in regions of much higher density. We will therefore briefly consider the case that the stellar orbits are purely radial.

Approximating the mass distribution in the bulge of M31 by that of an isothermal sphere, we obtain a fraction of time spent within a distance $r$ from the centre by a star with orbital extreme $r_{\text{max}}$

$$f(r, r_{\text{max}}) = 1 - \text{erf} \left[ \ln \left( \frac{r_{\text{max}}}{r} \right)^{1/2} \right], \quad (7)$$

where erf denotes the error function. As M31 has a well defined nucleus with radius 8 pc and mass density $2 \times 10^6 M_\odot pc^{-3}$ (for $\sigma = 150 \text{ km/s}$, Light et al., 1974), the effect of stellar encounters in this nucleus is much larger than anywhere else. A considerably shorter disruption time scale then follows as the density in eq. (6) can be replaced by $2 \times 10^6 f(8\text{pc}, r_{\text{max}}) M_\odot pc^{-3}$. To $r_{\text{max}} = 200, 100,$ and 50 pc correspond the values of $f 0.011, 0.025,$ and 0.056 respectively, so that $\tau_d(a=2 \text{ AU}) \leq 10^{10} \text{ yrs}$ for $r_{\text{max}} \leq 100 \text{ pc}$. Let us further assume that the novae in the bulge of M31 belong to the oldest stellar population (age $10^{10} \text{ yrs}$), and that only binaries with separations before spiral-in in the range 2 - 5 AU can become novae, where the upper limit of 5 AU is set by the Sirius system. The decrease of
the number of novae by widening or disruption of the orbits of potential
progenitors is then partially compensated by the widening of binaries with
initial separation less than 2 AU. An exact calculation, based on Heggie's
results and taking a distribution of binary separations proportional to
\( a^{-1} \) (van Albada, 1968), shows that the expected number of novae is reduced
by 35%, 50%, and 70% at distances \( r = 200, 100, \) and 50 pc respectively due
to stellar encounters in the high density nucleus of M31. A narrower range
of pre-spiral-in separations does not significantly increase the above
percentage. We recall that the observations indicate a decrease by as much
as 86% within 200 pc.

After spiral-in of the red dwarf in the giant envelope the nova progeni-
tors are hard binaries because they have separations \( a < 8.5 \, R_e \). The hardening
of hard binaries by stellar encounters occurs on a time scale (Heggie, 1975)

\[
\tau_h(r_{\text{max}}) = \frac{a}{\dot{a}}
\]

\[
= 1.6 \times 10^{12} \left( \frac{a}{1 \, R_e} \right)^{-1} \left( \frac{\rho}{2 \times 10^6 \, M_{\odot} \, \text{pc}^{-3}} \right)^{-1} \left( \frac{f(8 \, \text{pc}, r_{\text{max}})}{0.01} \right)^{-1} \left( \frac{\sigma}{150 \, \text{km/s}} \right) \text{ yrs.}
\]

(8)

The decrease of \( \dot{a} \) by gravitational radiation losses becomes larger than that
due to stellar encounters for separations

\[
a \leq 20 \left( \frac{\rho}{2 \times 10^6 \, M_{\odot} \, \text{pc}^{-3}} \right)^{-1/5} \left( \frac{f(8 \, \text{pc}, r_{\text{max}})}{0.01} \right)^{-1/5} \left( \frac{M}{M_{\odot}} \right)^{1/5} \left( \frac{\sigma}{150 \, \text{km/s}} \right)^{1/5} \, R_e,
\]

(9)
i.e. for all hard binaries. Finally the disruption time scale by stellar
encounters is much longer for hard binaries than for soft binaries.

From these arguments we infer that the nova hole filled by X-ray sources
has too large a size to be accounted for by stellar dynamical effects.
3.3.2 The age of the central stellar population in M31

The remaining possibility is that the more advanced evolution of nova-like binaries in the bulge is an age effect. This would imply that the central region of M31 consists exclusively of an old stellar population in which star formation terminated billions of years ago. That this may indeed be the case is supported by the fact that the central region of M31, unlike that of our Galaxy, shows no signs of star formation at present. In particular, there appear to be no OB supergiants (van den Bergh, as quoted in Wu et al., 1980), and no HII regions have been found nearer than 3 kpc to the centre (Rubin and Ford, 1971). As apparent from numerous studies (cf. Rieke and Lebofsky, 1979, and references therein) the optical and infrared energy distribution of the inner region of M31 is very similar to that of the nuclei of giant elliptical galaxies, and is due to an old metal rich stellar population with a main-sequence turn-off near \( 1 \, M_\odot \) and a metal abundance of once to twice the solar value. A large UV flux has also been detected (Wu et al., 1980 and references therein), which is probably contributed by blue horizontal branch stars rather than by young massive stars.

A comparison of all these observations with stellar population synthesis models indicates that most of the inner bulge population of M31 was formed about 8 to \( 11 \times 10^9 \) years ago, during a single star formation burst with an initial mass function close to the Salpeter function. It thus has an age in between that of the oldest open cluster and the youngest globular cluster in the Galaxy (Demarque, 1980).

The presence of about 30 hard X-ray sources in the Galaxy within 3 kpc from the centre, which are probably the same type of objects as the inner M31 sources, is not necessarily in conflict with our hypothesis: the population identification of sources between 400 pc and 3 kpc in M31 is by no
means unambiguous, and the number of sources observed there is sufficiently large to allow in M31 for the presence of a distribution of bulge sources similar to that observed in the Galaxy. Thus, the only respect in which the population of X-ray sources in M31 might differ from the one in our Galaxy is the presence of the cluster of strong bulge sources within 400 pc from the centre.

We conclude that the most likely explanation for the central nova hole filled by X-ray sources is that the stellar population in the core of M31 is essentially so old that most nova-like systems there have already evolved beyond the nova stage and eventually turned into X-ray sources.

4. DISCUSSION

4.1. The incidence of novae in star clusters and elliptical galaxies

It seems of interest to compare our M31 results to the available data for star clusters and other galaxies.

We first consider the situation in globular clusters which also belong to the oldest stellar population. The total stellar mass within 400 pc of the centre of M31, where the 18 bulge sources are located, is $\sim 2.5 \times 10^9 M_\odot$ (Rubin and Ford, 1970), i.e. there is one X-ray source per $1.4 \times 10^8 M_\odot$. Given a mean globular cluster mass of $5 \times 10^5 M_\odot$, the 355 globular clusters in M31 (Sargent et al., 1977) and the 125 galactic globular clusters constitute $1.8 \times 10^8 M_\odot$ and $0.6 \times 10^8 M_\odot$ respectively. Hence, if the incidence of X-ray sources and novae in the inner bulge of M31 and in globular clusters were the same, statistically at most one X-ray source in the M31 globular clusters and none in the galactic ones should be present, while novae should be absent. Yet X-ray sources have been detected in ten galactic and in sixteen M31 globulars, and 3 novae and 3 dwarf novae have been detected in galactic globular clusters (Trimble, 1977).
The presence of these objects in globular clusters can easily be ascribed to stellar dynamical effects which are insignificant in the bulges of galaxies (cf. section 3.1). Trimble (1977) pointed out that the higher than normal incidence of close binaries in globular clusters is much better explained by the (tidal) capture hypothesis than by a normal initial binary population. These binaries are then expected to be younger than the globular clusters themselves. Therefore the novae have not had time to evolve beyond the nova stage. It appears from the above that, despite superficial similarities between bulge sources and globular cluster sources in our Galaxy the formation mechanisms of globular cluster sources and the inner bulge sources in M31 must be entirely different.

No novae or dwarf novae have been observed in old open clusters (Kukarkin and Mironov, 1971). This is not surprising because of the small number of such clusters.

Three novae have been found in dwarf elliptical galaxies: one in NGC 147 and in NGC 185 (Baade, 1958), and one in NGC 205 (Zwicky, 1957). These are all close companions of M31. While NGC 205 and NGC 185 clearly show OB supergiants in their centres, NGC 147 seems to consist mainly of an old stellar population (Hodge, 1971). Since no more information is available, it is inferred from our present work that this last galaxy should not be older than the inner bulge of M31.

4.2. Some constraints on the lifetime of the X-ray stage in bulge sources

It seems useful, in the case that a real connection exists between the bulge X-ray sources and novae, to examine what the observed number of both kinds of objects would imply in terms of the lifetime of the X-ray emitting
stage. Let us consider the implication of the evolution of novae towards an X-ray stage. Pottasch (1959) estimated that $5 \times 10^{-5} \, M_\odot$ is ejected per nova outburst. We suppose that an equally large mass is definitively accreted onto the white dwarf per outburst. Then, for an accretion rate of $10^{-9} \, M_\odot$/yr, outbursts are expected to occur every $10^5$ years. Assuming that all white dwarfs are in nova systems, Ford (1978) estimated a minimum number of outbursts per nova between 160 and 660 from M31 statistics and theoretical deathrates of white dwarfs in the case that all white dwarfs are in nova systems. If only 10% of all white dwarfs are in binaries and become novae, a nova stage of about $5 \times 10^8$ years follows. An upper limit of $10^9$ years is inferred from the fact that the mass of the main-sequence star in nova systems is below solar. With an interval of $10^5$ years between two outbursts, and given that M31 was kept under constant observation for 15 years (Rosino, 1973), the number of nova binaries actually present is a factor $7 \times 10^3$ higher than the number observed during these 15 years. Suppose further that during the X-ray stage the source continuously emits X-rays (i.e. there are no off-stages). Then, if the X-ray sources in the inner bulge of M31 have evolved from the same type of objects which are still novae elsewhere in M31, the fact that their number is about equal to the number of novae expected from extrapolation of the nova distribution in the outer bulge, would imply that at least one out of every 7000 novae eventually becomes and X-ray source (exactly one if all such X-ray sources are still 'alive'). Or, alternatively, if all novae were to evolve into X-ray sources, that the X-ray stage lasts less than 7000 times shorter than the nova stage. Hence, the duration of the X-ray stage should be between $10^5$ and $5 \times 10^8$ years.
4.3. Age gradients

If the nova hole is an age effect, this implies that it takes at most a time equal to the age of the inner bulge of M31 for the nova phenomenon to occur after the progenitor binary system was formed. Hence all novae should be younger than 8 to $11 \times 10^9$ years. We have seen that this is not in conflict with the presence of novae in globular clusters and in a few dwarf elliptical galaxies. The novae can thus be classified as an intermediate population II or an old disk population, in good agreement with their scale height of about 200 pc and radial density gradient $d(\log v)/d(\log R) = -2.2$ in the galactic disk (Payne-Gaposchkin, 1957). An upper age limit for the nova phenomenon is also plausible because the progenitors of the white dwarfs in novae should be rather massive ($4 - 12 M_\odot$) and therefore have short stellar evolutionary time scales. It can then be concluded that most of the lifetime of the binary system prior to the nova stage is required for the binary separation to become sufficiently small so that Roche lobe overflow of the main sequence star ensues.

The fact that there is a sharp decline of the nova density towards the centre of M31 over 400 pc implies that there should be an equally sharp age gradient in this region. A significant age gradient over 400 pc can exist only if mixing of stellar orbits covers a radial distance much smaller than 400 pc. While a maximum velocity of 225 km/s has been measured for the gas at 400 pc (Rubin and Ford, 1970), the rotational velocity of the stellar component does not exceed 70 km/s (Pellet, 1976), so that the stars are supported mainly by their random energy.

For an isothermal isotropic velocity distribution the eccentricity $e = \frac{a - p}{a + p}$ of stellar orbits (with $a$ and $p$ the apogalactic and the perigalactic
distance, respectively) has a mean value of about 0.27 (Tremaine, 1976), which is equivalent to \( p = 0.57a \). Taking the mean radial distance of a star equal to \( r = \frac{1}{2} (a + p) \), we obtain a mean radial mixing length \( a - p \approx 0.54r \). This is sufficiently small to allow the existence of an age gradient.

The observed colour gradients (Sandage et al., 1969) and gradients in line features (Cohen, 1979; Faber and French, 1980; Persson et al., 1980) can be interpreted as due to changes in either metallicity or age. McClure et al. (1980) have argued that the observed spectral type variations in the nuclei of spiral galaxies are a metal abundance rather than an age effect, as is the case for elliptical galaxies. They define a spectral index and show that it is correlated with both the absolute magnitude of the bulges of spirals and with the total absolute magnitude of ellipticals in the same way. However, as evident in NGC 205 and NGC 185 (which are both included in their sample), as well as in our own Galaxy, star formation is certainly present in the central regions of some dwarf ellipticals and spirals. Hence besides the metal-poor horizontal branch stars, young stars should also contribute part of the ultraviolet light emitted by these galaxies. It is therefore inferred that metal abundance is not the only difference exhibited by the nuclei of spirals and dwarf ellipticals. Age effects are also important.

We finally note that, apart from the nuclei of giant elliptical galaxies, large spiral galaxies such as M81 have spectral energy distributions very similar to that of M31, so that the M31 nova hole may be a common characteristic of such galaxies.
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References

FIGURE CAPTIONS

Figure 1: The distribution of novae (open circles; Rosino, 1964, 1973) and bulge X-ray sources (dots; van Speybroeck, unpublished) in the central region of M31. Positions are shown in rectangular coordinates centered on M31, with the vertical direction corresponding to the major axis (P.A. 37°). The circles have radii of 1' and 2'.

Figure 2: The surface number density distribution of novae (solid histogram) in bins of 1' as a function of the distance from the centre of M31. The solid curve is the surface brightness distribution in blue light (de Vaucouleurs, 1958), where the distance from the centre has been taken as one-half the sum of the distances along the major and the minor axes. The nova and the surface brightness distributions have been fitted to each other with respect to their mean values between 2' and 8.5' as indicated. The mean surface brightness of approximately the first two bins is also shown (dotted lines).