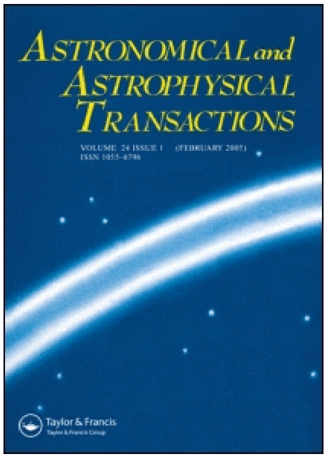

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OPTICAL AND NEAR-IR COLOR GRADIENTS IN THE CARTWHEEL RING GALAXY

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Using the stellar population synthesis model, we analyze color properties of stellar populations produced by ring waves of propagating star formation and compare our results with the radial $B-V/V-K$ color gradients observed in the archetype ring galaxy A0035-324, the Cartwheel. We find that young stellar populations, born from a ring wave of star formation propagating radially from the galactic center in a purely gaseous disk, exhibit much bluer colors than those observed in the Cartwheel galaxy. The presence of the older stellar populations extending up to the current location of the Cartwheel's outer ring is required to explain the observed radial color distribution in the galactic disk.

KEY WORDS Galaxies, colors, star formation

1 INTRODUCTION

Ring galaxies are believed to be the result of a head-on galaxy-galaxy collision. We assume that the galactic collision stimulates a self-propagating wave of star formation (Korchagin *et al.*, 1998), which is a self-organized phenomenon and is similar to the 'fire in the forest' model discussed by Seiden and Gerola (1982). Such a wave manifests itself by a bright optical ring of elevated H_α surface brightness. The analytical formulation of the model as well as the model parameters can be found in Korchagin *et al.* (1998) and Korchagin *et al.* (1999).

2 THEORETICAL MODELING OF THE CARTWHEEL'S RADIAL $B-V/V-K$ COLOR GRADIENT

As a wave of star formation advances radially from the galactic center, it leaves behind evolved stellar populations, with the youngest stars located at the current position of the wave. Thus, the star formation history should be preserved in the radial color distribution of stars behind the wave. Such color gradients were indeed found in the Cartwheel galaxy by Marcum *et al.* (1992). Recent observations of a sample of northern ring galaxies by Appleton and Marston (1995) show that most of them exhibit radial color gradients similar to the pattern observed in the Cartwheel.

To model the Cartwheel's B–V/V–K colors, we consider a circular wave of star formation propagating from the center of a galactic disk to the present location of the Cartwheel's outer ring at 16 kpc ($H_0 = 100\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$). The computational area is divided into 10 annuli as in Plate 1 of Marcum *et al.* (1992). The mass of stars formed in each annulus is distributed into individual stellar masses using the Salpeter IMF with $\alpha = 1.35$ and the stellar mass interval of $m_1 = 0.1M_\odot$ and $m_2 = 100M_\odot$. The luminosity of each annulus at a given band A after time t can be computed as:

$$L_A(t) = \sum_m \sum_{\tau_m} l_A(m, \tau_m) N(m, \tau_m, t), \tag{1}$$

where $N(m, \tau_m, t)$ is the number of stars in a given annulus at time t with mass m and age τ_m, and $l_A(m, \tau_m)$ is the luminosity of a star in the band A. Stellar luminosities $l_A(m, \tau_m)$ are obtained using stellar evolutionary (Schaller *et al.*, 1992) and atmospheric (Kurucz, 1992) models. The population synthesis technique used in this work is explained in detail in Mayya (1995, 1997).

3 RESULTS

As Higdon (1996) noted, low metal abundances and large H_α equivalent widths in the Cartwheel's outer ring are strong evidence for the first major episode of massive star formation (MSF) at this radius. Hence, the pre-collision Cartwheel was probably a small spiral embedded in an extensive mainly gaseous disk, much like the extreme low surface brightness galaxy Malin 1. The near-central galactic collision generated a wave of star formation, which propagates in a mainly gaseous galactic disk leaving in its wake the first major generation of stars exterior to the nucleus.

To imitate this, we consider a ring wave of star formation propagating in an exponentially decreasing gaseous medium of $\Sigma_{\mathrm{gas}} = 5.0\exp(-r/11) \times 10^7 M_\odot\ \mathrm{kpc}^{-2}$. The initial metallicity of gas was chosen to be one-fifth of the solar metallicity, as derived by Fosbury and Hawarden (1977) for the outer ring. The velocity of a propagating star formation wave is taken to be $v = 90$ km s^{-1} (Korchagin *et al.*, 1998). Stellar populations born from such a wave exhibit V–K colors of about 1.5 mag bluer as compared to the Cartwheel's colors, as shown in Figure 1 by the open squares. The filled triangles with error bars indicate the observed B–V/V–K colors of nine rings and nucleus in the Cartwheel's disk. The outer three annuli 9, 8, and 7 are identified both for the observed and model points. The model colors fail to reproduce the observed sequence of colors in the Cartwheel's disk.

We estimate the color excess $E(B - V)$ on the hypothesis that the difference of model and observed colors in Figure 1 is solely due to dust extinction. Using the

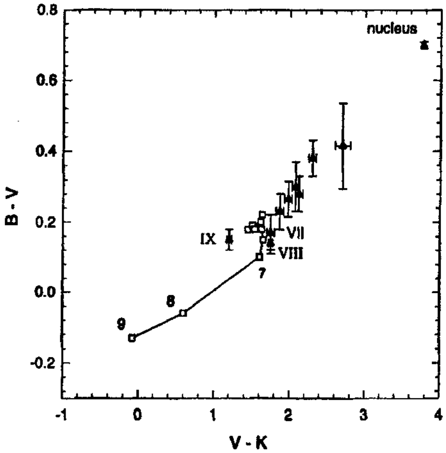

Figure 1 B–V/V–K color diagram of young stellar populations, born from a star formation wave propagating in a purely gaseous disk with an initial metallicity of $z = z_{\odot}/5$.

galactic dust-to-gas ratio we derive the expected surface densities of HI+H_2 (Bohlin *et al.*, 1978). The difference of colors of the three outermost photometric annuli (IX, VIII, VII) can in principle be attributed to dust extinction. The extinction-estimated gas densities at the inner annuli are higher than the detection upper limit and hence extinction cannot be responsible for the difference of model and observed colors in Figure 1.

The appearance of the pre-collision Cartwheel might be important for theoretical color interpretations. As the next step of color modeling, we consider the possibility that some MSF has taken place prior to the collision. As noticed by Korchagin *et al.* (2001), the Cartwheel's colors in B–V/V–K diagram lie approximately between the model colors of post-collision stellar populations (as shown by the open squares in Figure 1) and colors of most normal galaxies. This indicates that the Cartwheel's colors can indeed be obtained by mixing the post-collision stellar populations with the older stellar populations existing in the Cartwheel's disk before the collision. We assume that the V-band intensity of the pre-collision stellar populations has an exponential profile and hence the surface brightness $\mu_V(r)$ in mag arcsec^{-2} is given by the relation: $\mu_V(r) = \mu_V^0 + 1.086r/R_0$, where μ_V^0 is the surface brightness in the center of the disk, and R_0 is the scale length. Surface brightness profiles in two other bands μ_B and μ_K are then obtained from the observed colors of a sample galaxy UGC 01305 (de Jong, 1996). Our choice is dictated by the fact that the Cartwheel seems to lack any bulge and hence before the collision it was a late-type spiral galaxy.

Colors are a difference of logs of corresponding surface brightnesses and the same colors in principle can be obtained from different sets of surface brightnesses. Hence, color modeling cannot be considered separately from surface brightness modeling. Computations show that an acceptable correspondence of the model and the

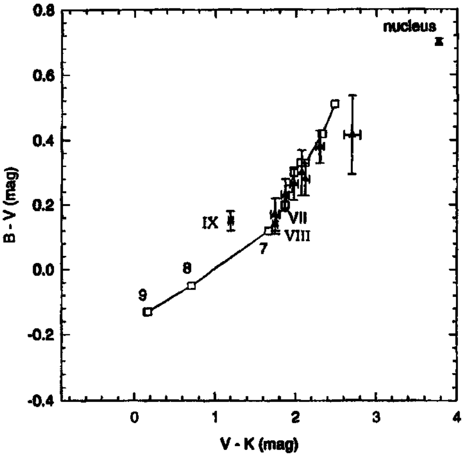

Figure 2 The model B–V/V–K color gradients of the Cartwheel galaxy. The observed colors are well reproduced by the mixture of young stellar populations and the old stellar disk of UGC 01305.

Cartwheel's radial surface brightness profiles in R and H_α (Higdon, 1995) can only be achieved for a rather low surface brightness pre-collision stellar disk of $\mu_V^0 \leq 23.5$ mag arcsec^{-2} and $R_0 = 5$ kpc.

The resulting color profile is plotted by the open squares in the color-color diagram in Figure 2. A metallicity of $z_\odot/5$ is used as described earlier in the text. It can be seen that the model colors of the mixed pre- and post-collision stellar populations correctly reproduce the observed sequence of colors in the Cartwheel's disk. As above, we estimate the color excess $E(B - V)$ on the hypothesis that the difference of model and observed colors in Figure 2 is solely due to dust extinction. The extinction-estimated gas densities at annuli II–IX lie below the detection upper limit and hence extinction may be responsible for the difference of model and observed colors in Figure 2. As to the nucleus and the inner ring (annulus I), their V–K colors are shifted too far to the red. More sophisticated models of propagating star formation in ring galaxies are needed to investigate this problem.

4 CONCLUSION

This paper focuses on the theoretical modeling of propagating star formation in ring galaxies with the purpose of interpreting the observed radial B–V/V–K color gradients in the Cartwheel galaxy. We assume that the Cartwheel is formed through a near-central galaxy-galaxy collision, which generated an outwardly propagating ring wave of star formation. We adopt the outer ring as the current location of such a wave, as indicated by elevated H_α surface brightness. Numerical simulations show that stellar populations born from such a wave of star formation can not account for the observed sequence of B–V/V–K colors in the Cartwheel's disk. Color modeling indicates that the Cartwheel must have an extensive pre-collision stellar disk of low surface brightness extending up to the current location of the outer ring at 16 kpc.

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