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E_∞-RING STRUCTURES FOR TATE SPECTRA

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1. Introduction

Let G be a compact Lie group and k_G a G spectrum (as defined in [3, Section I.2]). Greenlees and May ([2]) have defined an associated G-spectrum $t(k_G)$ called the *Tate spectrum* of k_G. They observe that if k_G is a ring G-spectrum, then there is an induced ring G-spectrum structure on $t(k_G)$, and that if k_G is homotopy-commutative, then $t(k_G)$ will also be homotopy-commutative (see [2, Proposition 3.5]). It is therefore natural to ask whether an equivariant E_∞ ring structure on k_G induces an equivariant E_∞ ring structure on $t(k_G)$ (we will recall the definition in a moment). We offer both positive and negative answers to this question.

On the positive side, we show that $t(k_G)$ inherits a structure which is somewhat weaker than an equivariant E_∞ ring structure, but which should be adequate for most practical purposes. To explain this we first recall that, given a G-universe U, there is an equivariant operad $\mathcal{L}(U)$ whose jth space consists of the (nonequivariant) linear isometries from $U^{\oplus j}$ to U. From now on we fix a complete G-universe U. By definition, an *equivariant E_∞ operad $\mathcal{C}$* is an equivariant operad which is equivariantly equivalent to $\mathcal{L}(U)$, and an *equivariant E_∞ ring structure* is an action of an equivariant E_∞ operad (see [3, Definition VII.2.1]). Next let us define an *E'_∞ operad* to be a nonequivariant E_∞ operad provided with trivial G-action. For example, if $\mathcal{C}$ is an equivariant E_∞ operad, then its G-fixed points form an E'_∞ operad $\mathcal{C}^G$ by [3, Example VII.1.4]. We define an *equivariant E'_∞ ring structure* to be an action of an E'_∞ operad (in other words, it is an action of a nonequivariant E_∞ operad through G-maps). Since any action by $\mathcal{C}$ restricts to an action by $\mathcal{C}^G$, we see that an equivariant E_∞ ring structure always includes an equivariant E'_∞ ring structure.

The reason why E'_∞ ring structures are interesting is that if k_G is an E'_∞ ring spectrum, then the fixed-point spectra $(k_G)^H$ have (nonequivariant) E_∞ ring structures which are consistent as H varies (see Remark VII.2.5 of [3]); this is likely to be the property one needs for applications.

Our positive result is:

Theorem 1. *If k_G is an equivariant E'_∞ ring spectrum, then so is $t(k_G)$; in particular all fixed-point spectra $(t(k_G))^H$ are nonequivariant E_∞ ring spectra.*

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The proof of Theorem 1 will show that the diagram in Proposition 3.5 of [2] is a diagram of equivariant E'_∞ ring spectra.

To state our negative result we need to recall the definition of $t(k_G)$. Let EG be a contractible free G-CW complex and let $\widetilde{E}G$ denote the G-space defined by the cofiber sequence

$$EG_+ \to S^0 \to \widetilde{E}G$$

(here + denotes a disjoint basepoint). Let $F(EG_+, k_G)$ be the function spectrum of maps from EG_+ to k_G ([3, Definition I.3.2]). Then $t(k_G)$ is defined to be the G-spectrum

$$F(EG_+, k_G) \wedge \widetilde{E}G.$$

Let us write ι for the natural map $S^0 \to \widetilde{E}G$.

Theorem 2. *Let G be a finite group and let k_G be any G-spectrum. Suppose that $t(k_G)$ has an equivariant E_∞ ring structure whose unit factors (up to equivariant homotopy) through $\sum_G^\infty \iota$. Then $t(k_G)$ must be equivariantly contractible.*

This implies that if k_G is a ring G-spectrum for which $t(k_G)$ is not equivariantly contractible, then $t(k_G)$ cannot have an equivariant E_∞ ring structure whose underlying ring G-spectrum structure is compatible with that of k_G under the natural map $k_G \to t(k_G)$. In particular, the underlying ring G-spectrum structure of $t(k_G)$ cannot be that defined in [3, Proposition 3.5]. Thus it seems that there is no natural way to give $t(k_G)$ an equivariant E_∞ ring structure.

I would like to thank Mike Hopkins for suggesting this problem to me and the referee for clarifying a point in the proof.

2. Proof of Theorem 1

Theorem 1 is an immediate consequence of the following two lemmas, of which the second is well-known. Let us recall from [3, Definition VII.2.7] that, given an equivariant operad $\mathcal{C}$, a $\mathcal{C}_0$ space is an action of $\mathcal{C}$ in the category of based G-spaces; that is, it is a based G-space X with based G-maps

$$(\mathcal{C}_j)_+ \wedge_{\Sigma_j} X^{(j)} \to X$$

(here $^{(j)}$ denotes j-fold smash product) satisfying the same compatibility conditions that are used to define an equivariant $\mathcal{C}$-space. In particular, this definition makes sense if $\mathcal{C}$ is a nonequivariant operad provided with the trivial G-action; it then says that $\mathcal{C}$ acts on X through G-maps.

Lemma 3. *There is a nonequivariant E_∞ operad $\mathcal{D}$ for which $\widetilde{E}G$ is an equivariant $\mathcal{D}_0$ space.*

Lemma 4. *Let $\mathcal{C}$ be any equivariant operad.*

(a) *If k_G is a $\mathcal{C}$ ring spectrum (that is, if it has an equivariant action of $\mathcal{C}$), then so is $F(Y_+, k_G)$ for any G-space Y.*

(b) *If h_G is a $\mathcal{C}$ ring spectrum and X is a $\mathcal{C}_0$-space, then $h_G \wedge X$ is a $\mathcal{C}$ ring spectrum.*

Proof of Theorem 1. Suppose that k_G has an action of an E'_∞ operad $\mathcal{C}'$. Let $\mathcal{C} = \mathcal{C}' \times \mathcal{D}$, where $\mathcal{D}$ is the operad of Lemma 3. Then $\mathcal{C}$ is an E'_∞ operad, and it acts on k_G (via the projection $\mathcal{C}' \times \mathcal{D} \to \mathcal{C}'$) and on $\widetilde{E}G$ (via the projection

$\mathcal{C}' \times \mathcal{D} \to \mathcal{D}$). Now Lemma 4(a) implies that $\mathcal{C}$ acts on $F(EG_+, k_G)$, and the theorem follows from Lemma 4(b) if we take h_G to be $F(EG_+, k_G)$ and X to be $\widetilde{E}G$. □

Proof of Lemma 4. In each case, we specify the structural maps which constitute the $\mathcal{C}$-action; the fact that they satisfy the necessary compatibility relations is a straightforward application of the methods of [3, Sections VI.1–VI.3].

For part (a) the structural map

$$\xi_j : \mathcal{C}_j \ltimes F(Y_+, k_G)^{(j)} \to F(Y_+, k_G)$$

is the adjoint of the composite

$$\begin{aligned} Y_+ \wedge \mathcal{C}_j \ltimes F(Y_+, k_G)^{(j)} &\xrightarrow{\Delta\wedge 1} (Y_+)^{(j)} \wedge \mathcal{C}_j \ltimes F(Y_+, k_G)^{(j)} \\ &\xrightarrow{\cong} \mathcal{C}_j \ltimes \left((Y_+)^{(j)} \wedge F(Y_+, k_G)^{(j)}\right) \xrightarrow{1\ltimes e} \mathcal{C}_j \ltimes k_G^{(j)} \xrightarrow{\xi'_j} k_G; \end{aligned}$$

here Δ is the diagonal map of Y, the isomorphism is that of [3, Proposition VI.1.5], e is the evaluation map, and ξ'_j is the structural map of k_G.

For part (b) the structural map

$$\xi_j : \mathcal{C}_j \ltimes (h_G \wedge X)^{(j)} \to h_G \wedge X$$

is the composite

$$\mathcal{C}_j \ltimes (h_G \wedge X)^{(j)} = \mathcal{C}_j \ltimes (h_G^{(j)} \wedge X^{(j)}) \xrightarrow{\delta} (\mathcal{C}_j \ltimes h_G^{(j)}) \wedge (\mathcal{C}_{j+} \wedge X^{(j)}) \xrightarrow{\xi'_j \wedge \xi''_j} h_G \wedge X,$$

where δ is the map given in Definition VI.3.5 of [3] and ξ'_j, ξ''_j are the structural maps for h_G and X. □

Proof of Lemma 3. First let us observe that $\widetilde{E}G$ is nonequivariantly contractible and that for any nontrivial subgroup H of G the H-fixed set $(\widetilde{E}G)^H$ is exactly S^0; the same is true for $(\widetilde{E}G)^{(j)}$ since the smash product of spaces commutes with H-fixed sets.

Let Map_*^G denote based G-maps. Restriction to the G-fixed set gives a map

$$\phi : \mathrm{Map}_*^G(\widetilde{E}G^{(j)}, \widetilde{E}G) \to \mathrm{Map}_*(S^0, S^0)$$

which we claim is a weak equivalence. Assuming this for the moment, let $\mathcal{D}'_j$ be the space $\phi^{-1}(\mathrm{id})$. Then the spaces $\mathcal{D}'_j$ with the evident composition operations γ form an operad $\mathcal{D}'$ and $\widetilde{E}G$ is a $\mathcal{D}'_0$-space. The only thing preventing $\mathcal{D}'$ from being a nonequivariant E_∞ operad is that the action of Σ_j on $\mathcal{D}'_j$ may not be free. To remedy this let $\mathcal{C}$ be any nonequivariant E_∞ operad and define $\mathcal{D}$ to be $\mathcal{D}' \times \mathcal{C}$, acting on $\widetilde{E}G$ via the projection $\mathcal{D}' \times \mathcal{C} \to \mathcal{D}'$.

It only remains to prove the claim that ϕ is a weak equivalence. First we observe that the reduced diagonal map

$$\Delta : \widetilde{E}G \to \widetilde{E}G^{(j)}$$

is a weak equivalence on each fixed-point set, and is therefore a G-homotopy equivalence by the equivariant Whitehead theorem. It follows that

$$\Delta^* : \mathrm{Map}_*^G(\widetilde{E}G, \widetilde{E}G) \to \mathrm{Map}_*^G(\widetilde{E}G^{(j)}, \widetilde{E}G)$$

is a homotopy equivalence, so it suffices to verify the claim when $j = 1$.

To handle this case, we map the cofiber sequence

$$EG_+ \to S^0 \to \widetilde{E}G$$

into $\widetilde{E}G$ to get a fiber sequence

$$\mathrm{Map}_*^G(\widetilde{E}G, \widetilde{E}G) \to \mathrm{Map}_*^G(S^0, \widetilde{E}G) \to \mathrm{Map}_*^G(EG_+, \widetilde{E}G).$$

The middle term is equal to S^0, so it suffices to show that the third term is weakly contractible. For this we recall that the functor $\mathrm{Map}_*^G(EG_+, -)$ takes G-maps which are nonequivariant weak equivalences to weak equivalences (for example, this follows from [1, XI.5.6] since $\mathrm{Map}_*^G(EG_+, -)$ is a special case of the holim construction). Since $\widetilde{E}G$ is nonequivariantly contractible, we see that $\mathrm{Map}_*^G(EG_+, \widetilde{E}G)$ is weakly contractible and we are done. □

3. Proof of Theorem 2

As motivation for the proof of Theorem 2, we first explain why the operad $\mathcal{D}'$ constructed in the proof of Lemma 3 is not equivalent to the linear isometries operad $\mathcal{L}U$. Let $G = Z/2$ for simplicity and consider the $G \times \Sigma_2$-spaces $\mathcal{L}U_2$ and $\mathcal{D}'_2$ (recall that $\mathcal{D}'_2$ has trivial G-action). Let H be the diagonal copy of $Z/2$ in $G \times \Sigma_2 = Z/2 \times Z/2$. We claim that $\mathcal{L}U_2$ has H fixed points but $\mathcal{D}'_2$ has none; this certainly implies that $\mathcal{L}U_2$ and $\mathcal{D}'_2$ are not $G \times \Sigma_2$-equivalent. To see that $\mathcal{L}U_2$ has H-fixed points we need only show that there is an H-equivariant linear isometry from $U \oplus U$ to U; but this is obvious since as an H-representation $U \oplus U$ is a complete H-universe, and is therefore H-isomorphic to U. (We note for later use that $(\mathcal{L}U_2)^H$ is in fact contractible by [3, Lemma II.1.5].) On the other hand, if $\mathcal{D}'_2$ had an H-fixed point, then there would be a $G \times \Sigma_2$-equivariant map

$$\widetilde{E}G^{(2)} \to \widetilde{E}G$$

(with Σ_2 acting trivially on the target) which extends the identity map of S^0, and passing to H-fixed points would give a (nonequivariant) map $(\widetilde{E}G^{(2)})^H \to S^0$ which extends the identity map of S^0. But this is impossible since $(\widetilde{E}G^{(2)})^H$ is contractible: there is a (nonequivariant) homeomorphism

$$\widetilde{E}G \to (\widetilde{E}G^{(2)})^H$$

which takes x to $x \wedge gx$, where g is the generator of G.

The proof of Theorem 2 is a variant of the same idea. For simplicity, we begin with the case $G = Z/2$. Suppose that $t(k_G)$ has an equivariant E_∞ ring structure whose unit η factors through $\Sigma_G^\infty \iota$. Then there is a G-homotopy commutative diagram of G-spectra

$$\begin{array}{ccccc}
\mathcal{L}U_2 \ltimes_{\Sigma_2} (S_G^0)^{(2)} & \xrightarrow{1 \ltimes \Sigma_G^\infty \iota^{(2)}} & \mathcal{L}U_2 \ltimes_{\Sigma_2} \left(\Sigma_G^\infty \widetilde{E}G\right)^{(2)} & \longrightarrow & \mathcal{L}U_2 \ltimes_{\Sigma_2} t(k_G)^{(2)} \\
\downarrow{\scriptstyle \xi_2} & & & & \downarrow{\scriptstyle \xi'_2} \\
S_G^0 & & \xrightarrow{\qquad\qquad \eta \qquad\qquad} & & t(k_G)
\end{array}$$

where ξ_2 and ξ'_2 are the structural maps for S_G^0 and $t(k_G)$. Next we recall that the upper-left corner of this diagram is an equivariant suspension spectrum, so that we may pass to the adjoint to get a G-homotopy commutative diagram of spaces. More precisely, [3, Proposition VI.5.3] gives an isomorphism

$$\mathcal{L}U_2 \ltimes_{\Sigma_2} (S^0)^{(2)} \cong \Sigma^\infty_G(\mathcal{L}U_{2+} \wedge_{\Sigma_2} (S^0_G)^{(2)})$$

which carries ξ_2 to the composite

$$\Sigma^\infty_G(\mathcal{L}U_{2+} \wedge (S^0)^{(2)}) = \Sigma^\infty_G(\mathcal{L}U_2/\Sigma_2)_+ \xrightarrow{\Sigma^\infty_G \pi} \Sigma^\infty_G S^0;$$

here π is the evident projection $(\mathcal{L}U_2/\Sigma_2)_+ \to S^0$. Thus the adjoint of the diagram above has the form

$$\begin{array}{ccccc}
\mathcal{L}U_{2+} \wedge_{\Sigma_2} (S^0)^{(2)} & \xrightarrow{1\wedge_{\Sigma_2}\iota^{(2)}} & \mathcal{L}U_{2+} \wedge \widetilde{E}G^{(2)} & \longrightarrow & \Omega^\infty_G(\mathcal{L}U_2 \ltimes_{\Sigma_2} t(k_G)^{(2)}) \\
\big\downarrow{=} & & & & \\
(\mathcal{L}U_2/\Sigma_2)_+ & & & & \big\downarrow{\Omega^\infty_G \xi_2'} \\
\big\downarrow{\pi} & & & & \\
S^0 & & \xrightarrow{\qquad\qquad\tilde\eta\qquad\qquad} & & \Omega^\infty_G t(k_G)
\end{array}$$

For our purposes, the important thing about this diagram is that $\tilde\eta \circ \pi$ factors, up to G-homotopy, through $\mathcal{L}U_{2+} \wedge \widetilde{E}G^{(2)}$. Precomposing with the projection

$$\mathcal{L}U_{2+} \wedge (S^0)^{(2)} \to \mathcal{L}U_{2+} \wedge_{\Sigma_2} (S^0)^{(2)},$$

we see that the composite

$$\mathcal{L}U_{2+} \wedge (S^0)^{(2)} = (\mathcal{L}U_2)_+ \xrightarrow{\pi} S^0 \xrightarrow{\tilde\eta} \Omega^\infty_G t(k_G) \tag{1}$$

(where we have again written π for the evident projection) factors up to $G \times \Sigma_2$-homotopy through $\mathcal{L}U_{2+} \wedge \widetilde{E}G^{(2)}$. Now let H be the diagonal copy of $Z/2$ in $G \times \Sigma_2$. Passing to the H-fixed points of (1) (and noting that the H-fixed points of $\Omega^\infty_G t(k_G)$ are the same as the G-fixed points since Σ_2 acts trivially), we see that the composite

$$(\mathcal{L}U_2^H)_+ \xrightarrow{\pi^H} S^0 \xrightarrow{\tilde\eta^G} (\Omega^\infty_G t(k_G))^G \tag{2}$$

factors up to (nonequivariant) homotopy through

$$\mathcal{L}U_{2+}^H \wedge (\widetilde{E}G^{(2)})^H.$$

But we have shown in the first paragraph of this section that $(\widetilde{E}G^{(2)})^H$ is contractible, so composite (2) is (nonequivariantly) homotopy trivial. We also showed in the first paragraph that $\mathcal{L}U_2^H$ is contractible, so π^H is an equivalence, and we conclude that

$$\tilde\eta^G : S^0 \to (\Omega^\infty_G t(k_G))^G$$

is homotopy trivial. This means that $\tilde\eta$ is G-homotopy trivial, and passing to the adjoint, we see that η itself is G-homotopy trivial. But η is the unit of the equivariant E_∞ ring $t(k_G)$, so $t(k_G)$ must be equivariantly contractible, as was to be shown.

So far we have assumed that G is $Z/2$. When G is finite of order n the action of G on itself by multiplication induces a homomorphism $\rho : G \to \Sigma_n$, and one can repeat the argument given above with $\mathcal{L}U_2$ replaced by $\mathcal{L}U_n$, Σ_2 replaced by Σ_n, and H replaced by the subgroup of $G \times \Sigma_n$ consisting of elements of the form $(g, \rho(g))$. □

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